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Exploring Team Dynamics: The Evolution of Coordination in a Complex Command and Control Environment

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EXPLORING TEAM DYNAMICS:

THE EVOLUTION OF COORDINATION IN

A COMPLEX COMMAND AND CONTROL ENVIRONMENT

A dissertation submitted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

By

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Daniel H. Schwartz ENTITLED Exploring Team Dynamics: The Evolution of Coordination in a Complex Command and Control Environment BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Doctor of Philosophy.

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ABSTRACT

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The present study explores the dynamic and emergent behavior of two teams, separately working through a synthetic task environment representing a battle management command and control domain under two levels of organizational centralization. While the manipulation of centralization had minimal effects on overall performance, evidence suggested that the need to seek authorization for actions from a central authority was a source of frustration. Both teams adapted over time, changing patterns of coordination to better meet the task demands. The results are discussed in the context of the concepts of normal accidents, high reliability organizations, and self-organization in complex organizations. Specific parallels between sensemaking in organization and perceptual-motor coordination (i.e., collaborative structures and smart mechanisms) are discussed.

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CHAPTER 1: INTRODUCTION

On April 14, 1994, two United States Air Force F-15s shot down two United States Army UH-60 Blackhawk helicopters over Northern Iraq during Operation Provide Comfort (Snook, 2000). The weather was clear, the electronic systems seemed functional, and the people involved were all highly trained and relatively experienced. The two Blackhawk helicopters were ferrying high-level personnel in and out of the No-Fly Zone (NFZ) of Northern Iraq while two F-15 aircraft were performing the first 'clean sweep' of the NFZ for the day, identifying low-flying targets. An Airborne Warning and Control System (AWACS; a surveillance and command and control (C2) aircraft that supports tactical and defensive fighter forces; Boeing, 2006) intermittently monitored the Blackhawk helicopters that were inside their Area of Responsibility (AOR) and ostensibly maintained command authority over the F-15s engagements. However, at the time of the 'clean sweep', the AWACS did not know where the Blackhawks were, and they had not informed the F-15 pilots of their potential presence. Ultimately, the F-15s misidentified the Blackhawk helicopters as Russian Hinds flown by Iraqis and shot them down, killing twenty-six people.

The AWACS mission crew were responsible for identifying, tracking, and controlling all aircraft flying through their AOR; for coordinating air re-fueling; for providing airborne threat warning and control in the AOR; and for providing surveillance, detection, and identification of all unknown aircraft (Levenson, Allen, & Storey, 2002). During the friendly fire episode mentioned above, multiple agents had confusing, overlapping responsibilities, and, with the addition of situation ambiguities, coordination failure ensued (Snook, 2000).

The situational complexities facing military teams in dynamic, time-sensitive environments such as AWACS environments require a high level of coordination in order to effectively manage an active battlespace. In addition to coordinating agent interdependencies, AWACS teams must manage pre-specified task and resource interdependencies, and adapt to unpredictable and ambiguous situations, such as those that led up to the friendly fire incident. Indeed, the friendly fire incident highlights the importance of managing both predictable and unpredictable organizational contingencies. To avoid similar military or comparable organizational disasters, it is crucial to understand how teams cope with uncertainties pertaining to system constraints, environmental variability, and agent interdependence.

The friendly fire event discussed above reveals the complexity of team-based C2 systems. The AWACS command and control work domain is part of a category of environments wherein social systems and technological systems are tightly interrelated (also known as socio-technical systems; Trist and Bamforth, 1951). The tight interrelationship between social and technological dimensions coupled with complex and dynamic, or continuously changing situations creates work domains that must be highly reliable and that can quickly adapt to varying contingencies. The first step in ensuring (i.e., designing, developing, evaluating) reliable and effective socio-technical systems is understanding the dynamics that form effective and ineffective system (e.g., team) functioning. Specifically, an understanding of how agents reliably learn and manage organizational constraints provides the foundation for designing, supporting, and protecting safety critical socio-technical systems. This research is an attempt to understand how teams manage dynamic uncertainty within a complex socio-technical domain – AWACS C2.

The following chapters approach managing organizational complexity as a problem of control. Specifically, highly reliable organizations cope with the demands of complex control problems by developing and utilizing effective control strategies. Chapter 2 discusses two approaches that seek to achieve a deeper understanding of the control demands of complex work domains: Normal Accident Theory (NAT) research and research involving High Reliability Organizations (HRO). Norman Accident Theory provides the foundation for defining complexity whereas HROs represent systems that are successful at continuously coping with complexity. It is argued that both perspectives are relevant to understanding the nature of complex control problems and solutions.

Although, NAT and HROs define complexity and characterize systems capable of reliably coping with uncertainty, neither approach elaborates on *how* organizations stabilize through complex and changing situations. Chapter 3 explores the role of sensemaking (i.e., continuous learning) as an adaptive process of stabilizing complex work domains. Several interrelated theories of learning are presented that illustrate *how* organizations continuously learn to manage complexity and instability. Specifically, theories of action and sensemaking are discussed as processes whereby organizations continuously learn reliable strategies for coping with dynamic situations.

Given the complexity of socio-technical systems such as the AWACS, particular scrutiny is given to the investigative research methods utilized to understand how stability is maintained. Thus, Chapter 4 discusses the emergent complexity of the AWACS C2 domain, the limitations of traditional (i.e., reductionistic) scientific methods, and the inherent difficulty in conducting empirical research onboard an active AWACS platform during battle management. Synthetic task environments (STE) are presented as pragmatic means of representing the relevant dimensions of the AWACS C2 work domain while maintaining a moderate degree of experimental control. Consequently, this research utilizes a synthetic task environment (STE) and AWACS mission scenarios, both based on cognitive work analyses (CWA) of the AWACS C2 work domain and a subject matter expert.

Chapter 5 explores quantitative and qualitative data patterns associated with continuous learning from both teams. Additionally, analyses and results are discussed relating to the effects of organizational centralization (centralization vs de-centralization) on performance and perceived workload. Finally, Chapter 6 reviews the implications of this study for the study, design, and development of socio-technical systems.

CHAPTER 2: NORMAL ACCIDENT THEORY AND HIGH RELIABILITY ORGANIZAIONS

The following chapter explores two complementary approaches to conceptualizing complex socio-technical systems – Normal Accident Theory (NAT) and High Reliability Organizational theory (HRO). Normal Accident Theory defines organizational complexity and highlights the necessity and difficulty of coping with uncertainty, whereas HROs represent systems that are successful at managing complexity. Both approaches are considered with the goal of achieving a deeper understanding of the control demands of complex work domains and the implications for organizational sensemaking.

Normal (i.e., inevitable) accidents are a characteristic feature of many complex systems (Perrow, 1984). A *system* is defined as an assemblage of interrelated elements or units that comprise an instrumental whole. An *accident* is a failure in a system "…that damages more than one unit and in doing so disrupts the ongoing or future output of the system" (Perrow, 1984; p. 66). Normal accident theory (NAT) focuses on the properties of specific systems that have potential for failure and how such systems recover from failure. However, NAT is limited in its conception of safety-critical systems vulnerable to so-called normal accidents.

High reliability organizations (HROs) represent an alternative conception of safety-critical organizations (i.e., used synonymously with the term 'system') that manage to avoid catastrophic failure (i.e., normal accidents) despite the presence of uncertainty and complexity (Roberts & Bea, 2001). While the NAT and HRO perspectives at first seem to be contradictory, both perspectives are relevant to understanding the nature of complex control problems and the potential solutions to these problems (e.g., Snook, 2000; Marais, Dulac, & Levinson, 2004).

Normal Accident Theory

According to Perrow (1984), complex systems exhibit both multifarious interactions and tight coupling as illustrated in Figure 2.1. Normal accidents are typically associated with systems in the upper right quadrant of the Interaction/Coupling chart. (e.g., nuclear power, chemical processes, genetic engineering). To consider why Perrow believes that accidents are inevitable in these systems, it is important to understand the dimensions of the space in Figure 2.1.

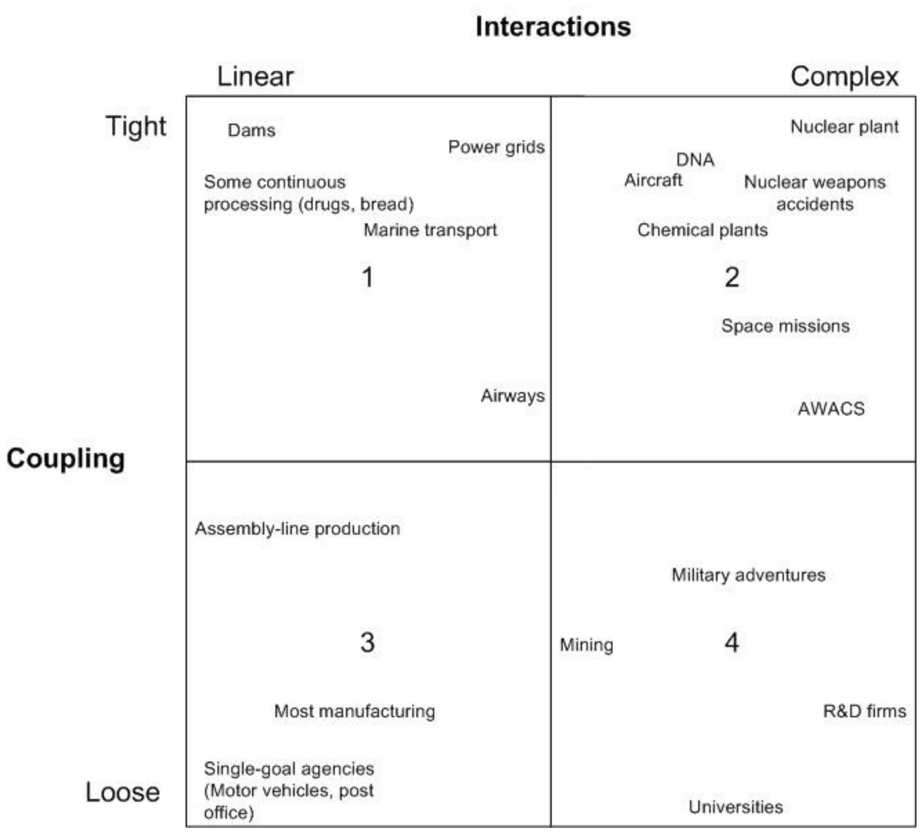


Figure 2.1. Interaction/Coupling chart where Quadrant 2 reflects the conditions that lead to normal accidents (Perrow, 1984, p. 97).

Interactions. The interaction-dimension of Perrow's space contrasts 'linear' with 'complex' systems. Where a linear system is one where the causal chains are relatively simple, making it possible to extrapolate both forward (to anticipate hazards) and backward (to diagnose faults). Dams and assembly lines are examples of systems dominated by linear interactions. At the other end of the continuum, a complex system is one where the causal chains are more convoluted (e.g., involving bifurcations and feedback loops) that make it more difficult to anticipate the consequences of an action and more difficult to trace back to identify the causes of a failure. Nuclear power plants and universities are presented as systems where interactions are complex. The accident at Three-Mile Island exemplifies a complex interaction that made it difficult to correctly diagnose a failure and thus to prevent a 'normal accident.'

Coupling. The coupling dimension of Perrow's space contrasts 'tight' with 'loose' coupling. Tight coupling indicates that there is no slack or buffer between components to prevent a problem in one part of the system from cascading to create a larger problem within the system. Dams and nuclear power plants are examples of tightly coupled systems. In such systems it is possible for a small leak in one component to cascade, leading to a catastrophic system failure. In loosely coupled systems, there are typically buffers (or, perhaps what Rochlin (1993) later refers to as 'friction') that can prevent the loss of the kingdom from the loss of a nail. Assembly line production systems and universities illustrate systems with loose couplings. For example in assembly lines, buffers along the line can help to prevent problems with machinery at one station from bringing the whole line to a halt. In universities, departments and even faculty within departments tend to function almost as independent agents, so that a failure of one department or one professor has little impact on the overall integrity of the system.

According to NAT, different conclusions can be made about systems plotted across the array in Figure 2.1. For example, universities are loosely coupled systems that exhibit relatively complex interactions. Thus, if something goes wrong, there are many potential solutions and there is time for recovery. Moreover, if something goes wrong, there are many unexpected interactions that transcend departments and roles (e.g., administrators, professors, students). On the other hand, nuclear power plants represent systems that are both tightly coupled and that exhibit complex interactions. Consequently, when something goes wrong in a nuclear power plant, there could be many unexpected and unforeseen interactions that transcend subsystems. Additionally, when failure occurs within a nuclear power plant, tight coupling (i.e., a lack of flexibility) limits the potential for corrective action increasing the possibility that an error will cascade. Thus, catastrophic accidents are a characteristic feature of systems that are tightly coupled and exhibit complex interactions (e.g., nuclear power plants; Perrow, 1984).

Systems characterized by both tight coupling and high interactive complexity, such as nuclear power plants, are inherently vulnerable to normal accidents (Perrow, 1984). However, as seen in the friendly-fire incident described earlier, complex systems with relatively *loose* coupling and high complexity also experience so-called normal accidents. Indeed, NAT focuses almost exclusively on complex systems based on relatively predictable and stable physical laws (and therefore tight coupling) as opposed to complex systems based on relatively unpredictable ecological dynamics and emergent behavior (where the couplings tend to be looser).

Re-Conceptualizing Normal Accidents

A problem with Perrow's space for characterizing systems is the two dimensions that characterize complex systems. Interactive complexity (i.e., failures in two or more discrete parts can interact in unexpected ways) and tight coupling (i.e., one part has high impact on another part) appear to be overlapping concepts. The degree to which two discrete parts interact in unexpected ways depends to some extent on the nature of the coupling between components. In other words, if a system's components have relatively little impact on other system components (i.e., loose coupling) then interactions may be minimized, but also these interactions can become more complex from the stand point of modeling and prediction. However, if a system's components greatly impact other components within the system, then interactive complexity will be high. Perhaps, Perrow's dimensions of interaction and coupling could be collapsed into a single dimension to reflect the nature of interactions between system components. Tight coupling would refer to 'linear' relations among the components so that the interactions between components are proportional or additive. Thus, the interactions are of the type that can, at least in principle, be modeled using typical linear principles and normative logic. Loose coupling would refer to systems with 'nonlinear' interactions that lead to emergent effects that are difficult to model using conventional normative assumptions.

Even when the interactions are 'linear' the system can be difficult to model if the number of components or dimensions becomes large (e.g., chess is an example where the combinations of possibilities challenge closed form optimal solutions and heuristics play an important role even in artificially intelligent systems). A second dimension that would be related to the overall complexity and thus, controllability of a system would be simply the number of components or parts. This suggests a second dimension for characterizing systems that will be identified as the ‘dimensionality’ of the system, as illustrated in Figure 2.2, which is proposed as an alternative to Perrow’s model.

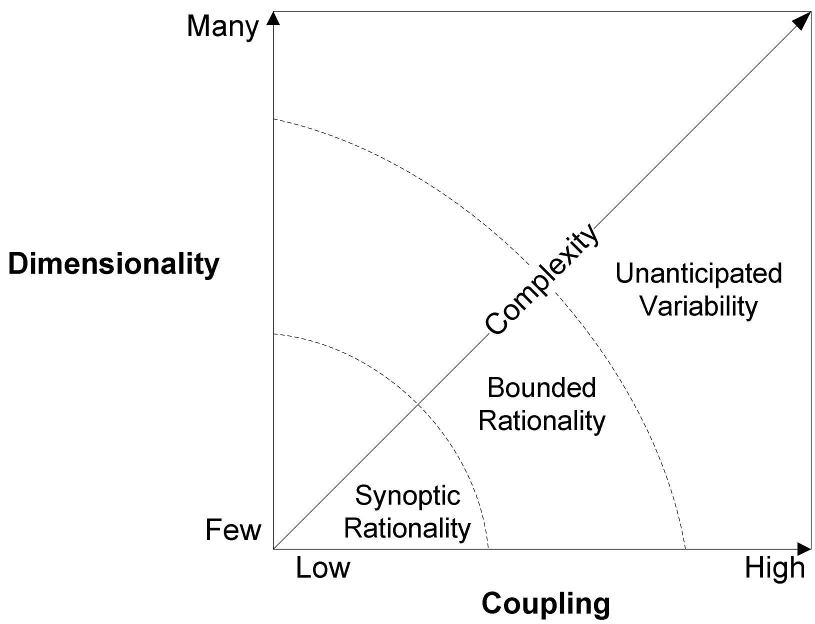


Figure 2.2. This is an alternative to Perrow’s (1984) interaction/coupling chart. The vertical axis reflects the number of dimensions of the system and the horizontal axis represents the degree of coupling.

Whereas Perrow’s space has complexity as a dimension of one axis (interaction), the alternative illustrated in Figure 2.2 envisions complexity as a joint function of the two dimensions. Complexity depends on both the number of dimensions and on the nature of the coupling among dimensions. The more dimensions a system has, the more complex it will be. For a given number of dimensions complexity further depends on the nature of the coupling, with linear systems being generally less complex than nonlinear systems. Thus, complexity increases along the diagonal from the lower left corner (few dimensions, linear coupling) to the upper right corner (many dimensions, nonlinear couplings).

The space illustrated in Figure 2.2 suggests three qualitative regions that have some relevance for the fundamental nature of the control logic or rationality. In low dimensional, tightly coupled systems, it is possible to specify the causal relations using normative, linear models. This region has been labeled the region of synoptic rationality (Lindblom, 1957). In the synoptic range, it is possible to specify optimal solutions base on classical engineering or economic analyses. When systems exhibit higher dimensionality and looser coupling, the assumptions of classical economic rationality may not be met or the solutions become intractable. In this range, control might be achieved using simplifying heuristics typical of what Simon (1957) called bounded rationality. However, as the complexity of the system increases, it becomes more and more likely that these heuristics will be defeated by unanticipated variability. Thus, a critical question that Perrow's analysis anticipates is the question of complexity. At what point, does complexity grow to a point where accidents due to unanticipated variability will be inevitable (i.e., normal)?

Note that the emergent dimension of complexity in Figure 2.2 is not necessarily synonymous with the stability of the system. As we will see, the overall system can be partitioned into the control 'problem' or the 'demands' of the work domain and the control 'solution' or the control 'strategy.' The control strategy reflects the organizational and human resources and the associated automatic control systems and decision technologies that support them. To a large extent, the stability of the organization will depend on the relationship between the demands of the work domain (i.e., requisite variety; Ashby, 1956) and the degrees of freedom in the controller or control organization. As Ashby notes, variety destroys variety. Thus, a very complex organization, such as a university, can be stable if the variety in the control organization offsets the variety associated with the control problem or work demands. On the other hand, when the flexibility of the control organization is less than the variability of the work demands, the total system may be 'brittle' as reflected in Vicente's (1999) striking example of the case of "malicious procedural compliance." In that case, exactly following procedures (working to rules) led to an infinite loop in an exercise in a nuclear simulator. The point of this example is that the procedures for control did not anticipate the variability of the work demands. This leads naturally to the research on high reliability organizations (HRO). In an important sense, a HRO is an organization that is able to achieve stability by matching the variability associated with the complexity of work demands through a comparable complexity (flexibility) in the control organization.

High-Reliability Organizations

As opposed to investigating systems to determine how they can, or eventually will, catastrophically fail (i.e., Normal Accident Theory), scientists that study high reliability organizations (HRO) seek to gain insights into how complex organizations *succeed* (i.e., manage to avoid catastrophic accidents) despite the challenges of having to deal with a complex problem with many components and the potential for nonlinear interactions (Weick & Roberts, 1993). In other words, HRO researchers attempt to understand complex, loosely coupled, and unstable systems that are defined by their resilience to error. Indeed, many of the systems that HRO scientists study do not fall within the quadrant of Perrow's space where normal accidents are to be expected due to loose coupling. AWACS, for example, are successful because their systems are intentionally loosely coupled in order to afford flexible opportunities for control. Additionally, AWACS systems are designed with built-in redundancies (e.g., redundant visual displays; open-radio channels; confirmation policies) wherein Weapons Directors can spot potential errors in other operators' behavior. Further, AWACSs' Air Tasking Orders that list all planned airborne activity in an area of responsibility (AOR) are coupled with aircraft identification of friend or foe (IFF) systems and fighter aircraft visual contact policies to ensure that mistakes, like the friendly fire incident mentioned above, do not occur. However, despite loose coupling, complex organizations like AWACS are clearly vulnerable to so-called normal accidents as illustrated by the friendly fire accident described by Snook and others (Shrader, 2005; Regan, 2004).

Laporte (1996) argues that HROs are a source of important lessons for how all organizations can minimize error and adapt to high demands. For example, HROs support an organizational culture of *mindfulness*. Weick and colleagues define mindfulness as an "enriched awareness…[through] active differentiation and refinement of existing categories and distinctions…creation of new discontinuous categories out of the continuous stream of events… and a more nuanced appreciation of context and alternative ways to deal with it" (1999; p. 90). The authors argue that mindfulness is the foundation for high reliability organizing because people in HROs attempt to 'see' more, make better sense of what they 'see', and remain attuned to their current situation (Weick & Sutcliffe, 2001).

Weick and Suttcliffe (2001) have discovered five attention-related processes that repeatedly emerge from analyzing HROs: 1) a preoccupation with failure/mistakes (e.g., constantly thinking about ‘missing something’), 2) a reluctance to simplify complexity (e.g., thinking about *all* possible failure modes), 3) sensitivity to operations (e.g., understanding the constraints inherent to process control), 4) a commitment to resilience (e.g., improvising and acting without knowing immediate consequences), and 5) a respect for expertise (e.g., letting decisions make their way to those with appropriate expertise to make them; Weick & Sutcliffe, 2001). The authors note that organizations that are not mindful develop ‘blindspots’ in their attention to the aforementioned HRO processes. Examples of events that emerged from organizations failing to be mindful include the Columbia accident (NASA, 2003), the friendly fire incident over Northern Iraq (Snook, 2001), and the hurricane Katrina catastrophe (Independent Levee Investigation Team, 2006).

The quantity of HROs that do not fall within the ‘significant’ zone of Perrow’s dimensional space is large and represents organizations that are critical to understand due to safety (e.g., air traffic control) and mission concerns (e.g., AWACS). The above re-conceptualization of Perrow’s complexity space (Figure 2.2) renders HROs as complex systems of critical concern. (To be sure, due to many degrees of freedom and loose coupling, attempts to understand the dynamics of HROs is rare compared with tightly coupled systems based on predictable physical laws [i.e., systems of critical concern for Perrow]). However, while observations and descriptions of HRO’s suggest that stable control is possible in complex work domains, it is very difficult to generalize from these observations without considering more fundamental aspects of control systems. Thus, the next section will consider the relation between complexity and stability in the context of a control perspective.

Control Systems

Control Problems vs Control Solutions

Control is a relation of constraint of one element by another (e.g., the pilot controls the aircraft). Control systems, such as HROs, can be differentiated into control *problems* and control *solutions*, wherein the control problem refers to the computational demands of a work domain and the control solution refers to the organizational strategies for meeting those demands. There are several, simple examples to make this important differentiation clear: process-control in nuclear power plants (i.e., control problem) is addressed through different power plant designs (i.e., control solutions); There are 32 different teams (i.e., control solutions) that play football (i.e., control problem) in the National Football League; there are four 'Big' international accountancy and professional service organizations (i.e., control solutions) that handle most audits for publicly traded companies (i.e., control problem). From these examples, it should be clear that the control problem and control solution transact to form the particular organization or system under consideration (e.g., CANDU Nuclear Power Plants, the NY Giants, Ernst & Young Accountancy). In other words, any particular organization or system includes both those constraints arising from the functional problem or work domain and those constraints arising from the people and automated systems that regulate processes within that domain - the stability of the total system will depend on the fit between these two system components.

Focusing on the control problem without considering the control solution, or visa versa, is a critical mistake when attempting to understand organizations. For example, when attempting to understand the corporate accounting services firm Ernst & Young as a system, it may be valuable to distinguish between the demands associated with corporate accounting (that pose challenges for any corporate accounting firm) and the specific constraints associated with the Ernst & Young organization. In this sense, the Ernst & Young organization reflects one of potentially many solutions that might satisfy the demands of this work domain. In a formative analysis, one might evaluate how good a fit the Ernst & Young organization is to the work demands. This may require comparisons between the Ernst & Young organization and other organizations (e.g., KPMG, PricewaterhouseCoopers) and/or it might require comparisons to normative (i.e., average or expected) control strategies derived from analysis of the work demands independent of any existing solution

When considering a successful control solution in relation to a particular control problem (i.e., a specific organization or system), it is useful to think about how a key unlocks a door. A key (i.e., control solution) for unlocking a door (i.e., control problem), acts on a specific lock within a particular door (i.e., characteristics of the 'work domain'). In order to open the lock, the key must have sufficient 'variety' in its key-structure to unlock the particular door (note: the ridges on the key). Indeed, according to the *law of requisite variety*, "the variety in the control system must be equal or larger than the variety of the perturbations in order to achieve control", (Ashby, 1958; cited in Heylighen, 1992). Thus, the variety of any control solution (e.g., door key, organization) must at least match that of the control problem (e.g., door lock, work domain). However, unlike the key metaphor, where the requisite variety is fixed in time, in many natural work demands the demands will vary over time and meeting these demands will require a key that can change (i.e., adapt) to fluctuating demands.

Ashby (1956; 11.4 ex. 4) provides a 'real-world' example of the *law of requisite variety*:

> A guest is coming to dinner, but the butler does not know who. He knows only that it may be Mr A, who drinks only sherry or wine, Mrs B who drinks only gin or brandy, or Mr C who drinks only red wine, brandy, or sherry. In the cellar he finds he has only whisky, gin, and sherry. Can he find something acceptable to the guest, whoever comes?
>
> He can get by, but if a hypothetical Ms D turns up, who drinks only wine or brandy, he can't cope and will be out on his ear, as indeed he should be: what kind of butler has no wine in the cellar?

In Ashby's example, the guests represent the control problem whereas the butler together with his cellar of resources represents the control solution. Unfortunately for the butler, he does not have a sufficient variety of alcohol to accommodate all the possibilities. Thus, in this case, the control solution will eventually fail – and the butler will face the consequences.

It is important to reiterate that organization, as a whole, represents the relation of constraint of a work domain (i.e., control problem; e.g., corporate accounting) by a particular control solution (e.g., Ernst & Young). In order to consider how the variability in control solutions fit with the demands of control problems, each component must be further parsed into three classes of constraint: value constraints, action constraints, and information constraints (See Figure 2.3).

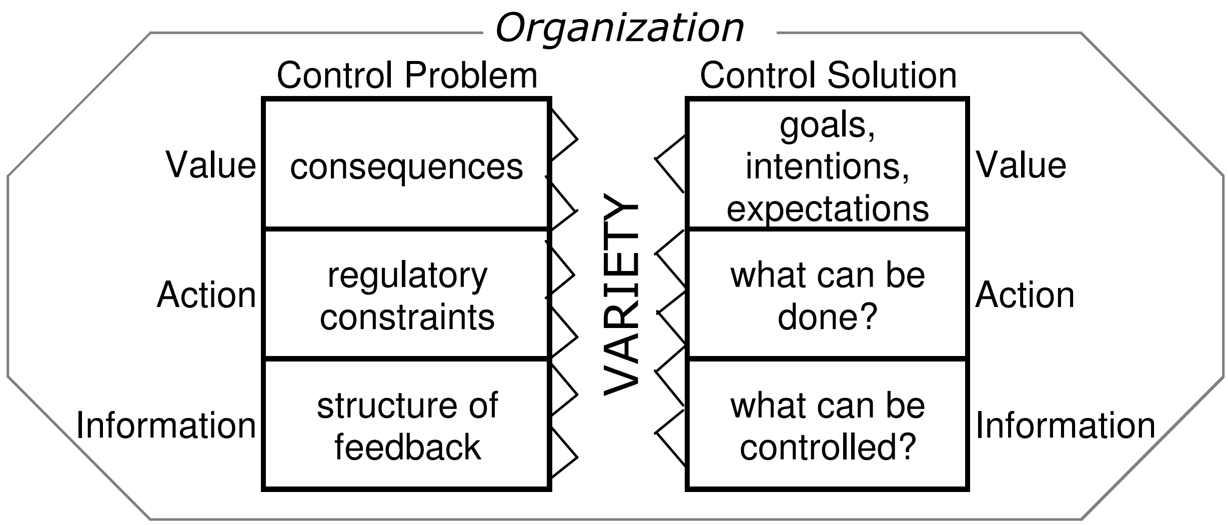


Figure 2.3. The overall system is partitioned into the problem and solution and each of these components is further partitioned to reflect three qualitatively different sources of constraint: values, actions, and information.

Value Constraints

Value constraints, to a certain extent, provide the fundamental reason why a system is of interest – that is, they reflect the purpose of the system. On the problem side of the equation this reflects the possible consequences for good or ill. For example, in a power plant some of the consequences would include the energy and the waste produced, the resources consumed, the likelihood and consequences of accidents, and the economics in terms of potential costs and profits. On the solution side of the equation this reflects the intentions or goals of the organization. This might reflect organizational priorities in terms of profits and risks that are deemed desirable or acceptable. It could also reflect specific targets for production, profit, or safety. It should be fairly obvious that the stability of the system will in part depend on the relation between the possible consequences (e.g., the likelihood of accidents and the costs associated with those accidents) and the priorities of the organization (e.g., the attitudes toward risk and the attention given to safety measures). A system operating in a work domain with high risks will not survive long if safety is not given a high priority. On the other hand, a system fixated on avoiding risk at all cost may fail due to economic constraints. Thus, stability will depend on the ability to find a balance of priorities that matches the balance of opportunity and risk in the work domain.

Action Constraints

Constraints on action within a work domain represent what *the system can do*. On the problem side of the equation, action constraints represent the possible moves or motions of the system. Typically, the possibilities within the work domain are constrained by physical laws (e.g., the laws of motion or of mass/energy balances) and by the regulatory environment (e.g., legal restrictions, and industry/cultural standards of behavior). On the solution side of the equation, action constraints represent the degrees of freedom in the organization. This reflects the independence and flexibility of the organization to make and carry out decisions. For example, in a hierarchical organization, the degrees of freedom are typically constrained to conform to plans generated by a centralized decision maker. Alternatively, a heterarchical system gives more freedom to individuals to react based on local contingencies without authorization from a central authority. Rochlin (1997) discusses the relative benefits of different styles of organization within the military domain (e.g., flat, de-centralized organizations versus vertical heterarchical organizations).

Again, it should be apparent that stability of a system will depend in part on the match between the possibilities in the problem space and the degrees of freedom of the control organization. If the degrees of freedom in the organization are more tightly constrained than the space of possibilities, then some possibilities will be difficult to realize and/or difficult to avoid. While increasing degrees of freedom within the organization will generally increase the sphere of stable possibilities, these increased degrees of freedom also increase the overall system complexity and can increase the overall computational demands of control. Here the challenge of stability typically depends on balancing the number of degrees of freedom against the dimensionality of the problem space, and the computational demands of control. Runeson's (1977) concept of *smart mechanism* provides an interesting discussion of how biological systems may find a dynamic balance that allows both flexibility and stability. Specifically, Runeson suggests that perceptual mechanisms are 'smart', meaning that they take advantage of idiosyncratic, situation-specific circumstances in the interests of efficiency and reliability in task performance. In other words, smart mechanisms maintain stability by modulating degrees of freedom relative to situation specific variety.

Thompson's (1967) classical analysis of organizations has some relevance to the challenge of managing degrees of freedom within an organization to meet the demands of the work domain. He described three types of interdependence: pooled interdependence, sequential interdependence, and reciprocal interdependence. *Pooled interdependence* describes a situation where movement in the problem space or work domain depends on a simple integration of the actions of the individual components (degrees of freedom) within the organization. While success may depend on a contribution from each degree of freedom in the organization, the individual degrees of freedom are relatively independent of each other. This kind of interdependence typically depends on some degree of standardization that allows the products to 'add-up' to reach a common goal. For example, the contributions of the strength coach, the travel office, and grounds keepers are all important to the overall success of a pro football organization. However, there is minimal coupling in terms of how each does their individual work. Or, consider a large corporate accounting organization that typically depends on many individual services (e.g., auditing, assurance and advisory, transaction advisory) that function independently to satisfy specific problems within the complex work environment. Standardization of methodologies, tools, and language, regardless of location, is essential for these components to work together

Sequential interdependence describes a situation where the work demands impose precedence constraints among the individual degrees of freedom. For instance, some parts of the organization may not be able to contribute to the systems goals until they receive products created by other components. For example, in Ernst & Young, the various service departments (e.g., fraud detection, internal audit) may have to carefully plan their individual analyses so that different service departments can utilize the analyzed information (e.g., fraud detection services utilize results from internal audit services). In the case of combat air operations, fighter aircraft may be required to give priority to specific enemy targets based on an Air Tasking Order that is disseminated by an AWACS. This type of interdependence often requires some degree of planning so that the individuals can all be on the same page – the fighter pilots and the AWACS know where the priority targets are located and requisite resources are allocated to complete the mission.

Finally, *reciprocal interdependence* refers to work domains where "…the outputs of each [component] become inputs for the others", (Thompson, 1967; p. 55). Thus, within reciprocally interdependent work domains, the behavior of each 'part' is contingent upon the behavior of other parts. In the case of Ernst & Young, success in managing a major corporation's tax risk may depend on reciprocal interdependence between tax risk assessors and internal auditors. That is, each may be forced to adapt to a changing corporate regulatory environment that may often depend on the ability to mutually adjust to each other. For example, given the increasing pressures on time and resources since the implementation of Sarbanes Oxley s404, many tax functions must manage their risk profile by inter-relating the tax technical skills of the tax function with the process and controls experience of the internal audit department. Or, in the case of combat air operations, the ability to respond to an emergent mission, such as rescuing a downed pilot, may require both the fighter and tanker to go outside the plan and to mutually adjust to meet the demands of the situation.

Note that the different types of independence (pooled, sequential, and reciprocal) and the associated coordination demands (standardization, planning, and mutual adjustment) are typically all involved in the solution of complex problems. Thus, to some extent each service department of a corporate accounting team makes a pooled contribution that is relatively independent and that reflects their specific standard skills. However, these skills are organized according to fixed plans (i.e., functions) that allow each to synchronize their actions to correspond with the actions of others (e.g., the tax audit department hands off the results of their analyses to the fraud detection department). However, these functional relationships typically do not completely specify all the actions. They typically include options that depend on local contingencies (e.g., changes in corporate regulatory environment) and that require service departments to make real time adjustments based on the actions of other departments (e.g., the business tax compliance department relying on up-to-date regulatory information from the transaction tax department). Similarly, the success of air combat operations depends on standardized connections so the aircraft can mate with the tanker to take on fuel, careful plans to insure that the necessary fuel required for the missions is available at the right place and the right time, and the ability for multiple components to adapt in real time to the dynamic opportunities and threats that were not anticipated in the original plans.

With respect to the complexity space illustrated in Figure 1.2, standardization and planning will be most useful in the regions of synoptic and bounded rationality and at least in the region of synoptic rationality these types of coordination may be sufficient. However, in the region of unanticipated variability, stability will hinge on the capacity for mutual adjustment. And that leads naturally to the third critical dimension for control, the dimension of information.

Information Constraints

Information constraints reflect feedback that enables controlled action. That is, the information constraints will allow actions to be monitored and adjusted relative to the goals and values of the system. From the problem side of the equation, the information constraints reflect the distinctions that are available to be measured. What can be known about the work domain? And most significantly, what information is relevant for evaluating the state relative to the purposes to be achieved. For example, in the context of corporate accounting, we are most interested in information that is relative to satisfying regulatory requirements and ensuring that our tax strategy meets our business needs. This may involve information about the strengths and weakness of our own corporate accounting standards and strategies. Is our current tax strategy working or do we need to make changes? From the solution side of the equation, the information constraints reflect the perspicuity and attentiveness of the organization. What aspects of the work domain is the organization aware of? For example, if an organization's tax department fails to take advantage of research and development expenditure credit claims on expenditure incurred in the year, this may have a real financial impact on the organization's current tax charge for the year (as a result of lost tax benefits). Furthermore, there may be no future opportunity to rectify the error if the relevant deadline has subsequently passed. A term commonly used to reflect the coupling of these two constraints is situation awareness. Where high situation awareness is used to characterize a person or organization who is aware of the critical domain distinctions that are relevant for critical decisions and low situation awareness reflects a person or organization who is out of touch or overwhelmed by the information.

It should be clear that the different types of interdependence and coordination described by Thompson have important implications for the types of information that will be valuable (i.e., to guide controlled action). Standardization of sequences and plans achieves coordination through establishing norms, schedules, work processes, and specific output goals. For example, in order for a car assembly line to function within standardized organizational output goals, executive operators require information related to the number of cars coming off the assembly line per day. Similarly, individual process operators require information regarding specific work process standards (e.g., time constraints) in order to work according to plan.

The lack of uncertainty and limited degrees of freedom within standardized organizations limits the dimensionality or variety of meaningful information. Thus, information regarding ‘How many?’, ‘How fast?’ are meaningful values for determining the stability or effectiveness of organizations such as assembly lines. In other words, due to the relative behavioral predictability of standardized organizations, such as assembly lines, simple metrics provide practical information related to the relative ‘health’ or performance of the system. As mentioned above, coordination through standardization and planning are most useful when a control problem has limited dimensionality and is relatively predictable (i.e., the region of synoptic rationality). On the other hand, when work domains are characterized by uncertainty and many degrees of freedom (e.g., AWACS), stability and predictability cannot be assured by standardization or by planning - stability will depend on the capacity for mutual adjustment.

Mutual adjustment achieves coordination through continual integration wherein agents are jointly responsible for decision-making and outcomes. In other words, reciprocally interdependent agents work together (e.g., share information, influence) to reduce uncertainty in order to make better decisions for the ‘common good’. For example, in combat air operations, AWACS WDs, fighter pilots, and the air operations center (AOC) must continuously share information related to possible enemy air targets. Thus, an AWACS radar system may indicate an unknown track within its area of responsibility. Indeed, the AWACS IFF system identifies the unknown track as an enemy aircraft. Additionally, the 72-hour air tasking order does not indicate any scheduled friendly aircraft for that location. Consequently, the AWACS consults the AOC to determine if any aircraft was recently scheduled to be at that particular location in the AOR. At the same time, an AWACS WD contacts a friendly fighter to obtain visual contact with the unknown track to determine, for sure, that it is an enemy target.

During this time-critical period, the AWACS WDS, the AOC, and the friendly fighter pilot continuously exchange information regarding the unknown aircraft's position, possible identity, and potential actions. The AOC determines that they do not have any friendly aircraft scheduled to be in that particular location within the AOR during the next 24-hours. However, through a rapid fly-by, the friendly fighter pilot visually determines that the unknown track is not an enemy fighter, but a civilian passenger jet that has veered off its standard course. Later, it is determined that the civilian passenger jet was attempting to avoid a dangerous weather system.

In combat air operations, each component (e.g., the fighter, AWACS, AOC) must know what other components are doing, in real-time. For example, prior to ordering a fighter to shoot down an unknown track, AWACS WDs must determine if the unknown track is a scheduled friendly outfit that they were not informed of. Consequently, the AWACS WDs maintain real-time communication with the AOC to ascertain if there were any errors or omissions in the ATO or, if somewhere up the command line someone ordered a friendly mission in the area of the unknown track. At the same time, the AWACS WDs order a fighter aircraft to maintain visual contact with the unknown track to determine its intent. Under these circumstances, many things can happen – the fighter might spot a cluster of enemy fighters, wherein the AWACS WDs will rapidly have to assign fighter reinforcements and inform the AOC; the AOC might establish that a Red Cross medical airlift was scheduled at the last minute to be in the area, wherein the AWACs will have to inform the fighter to be extra cautious NOT to fire when conducting a visual fly-by. Ultimately, each component (i.e., the fighter, the AOC, the AWACS WDs) is a potential source of unanticipated variability for all other components. This variability must be matched by requisite variety in the feedback loop to allow mutual adjustment.

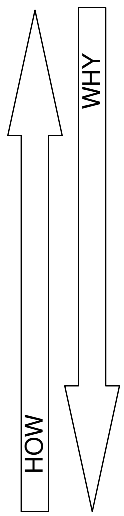
Voice loops are an example of a feedback loop that allows mutual adjustment through space shuttle mission control by affording synchronous communication among spatially distributed agents (Patterson, Watts-Perotti, & Woods, 1999). Voice loops that are structured around a mission control organization allow agents to listen in on relevant communication without disrupting their own activities or the activities of others (Patterson, Watts-Perotti, & Woods, 1999). Additionally, the variety afforded by voice loops allows agents to coordinate their efforts in real-time, in response to dynamic situations. If something that is transmitted on the voice loops does not match an agent's expectations, attention can be diverted to the discrepancy to investigate potential problems. For example, if a controller hears about a failure within one subsystem, they can assess the relative impact on their subsystem and anticipate any actions that might be required of them. Similarly, an operator can listen in on the relative tempo of communication through a voice loop to determine the relative workload of other operators or the status of specific processes. Thus, voice loops support mutual adjustment by behaving like a dynamic 'window' through which processes and activities of agents and subsystems can be viewed.

In order to design or develop a stable system, the meaningful constraints of the control problem (i.e., work domain) must be made apparent to the control solution. Specifically, systemic stability is predicated on the ability of a controller (e.g., agent) to reduce the discrepancy between feedback about the current state of a system and the values inherent to the system. Thus, an agent's control solution for stabilizing a system is based on an understanding of organizational values, feedback representations, and opportunities to act; i.e., the meaningful constraints of the work domain. One approach to systematically uncovering what information is significant to stabilize a particular complex system, such as combat air operations, is Cognitive Systems Engineering.

Cognitive Systems Engineering (CSE)

Cognitive Systems Engineering represents an approach to systems design that utilizes both analysis of work domain constraints (i.e., control problems) and analysis of potential strategies (i.e., control solutions) to inform the development of process and technology for human-system integration (i.e., control solutions; Rasmussen, 1994; Vicente, 1999). The goal of CSE is to improve the fit between work domains and the people and technologies that manage them. In other words, the goal is to enhance system stability through improved human systems integration.

Work domain analysis. According to CSE principles, the first step in understanding a work domain or control problem is to conduct a work domain analysis. The purpose of a work domain analysis is to develop a functional map of the means-end relations within a work domain, where the ends reflect the functional purposes and the means reflect both the action constraints and the information available for guiding that action. This is accomplished by developing an abstraction hierarchy/decomposition (Rasmussen, 1994; Vicente, 1999; see Figure 2.4 for an example of an AWACS abstraction hierarchy). The abstraction hierarchy can be seen as a way to view a complex system through different levels of magnification – e.g., microscopic – macroscopic. The abstraction hierarchy is a means-ends description of a system whereby higher-levels describe the ‘why’ or higher order functionality of the system, and lower-levels describe ‘how’ or the means through which high-level functions are achieved.



Functional Purpose	Early warning & control of events in assigned area of responsibility			
Abstract Function	Knowledge of regional activities	Establish, update, and disseminate tactical picture	Exercise control	Preserve platform, sensors, information systems
General Function	Detect, track, and associate	Evaluate tactical situation	Communicate	Implement protective measures
Physical Function	Gather data	Store and process mission data	Exchange information	Provide protection
Physical Form	Radar	Mission processing computer	Radio voice links	Radar warning receiver

Figure 2.4. A sample of functions from each layer of an AWACS abstraction hierarchy (adapted from Naikar, et al., 2000).

The highest level of abstraction is the functional purpose, or the ultimate reason that the system exists. The highest level delimits ultimate goals to be achieved and environmental constraints that need to be recognized. For example, the functional purpose of an AWACS is early warning and control of events in an assigned area of operations. In other words, within a specified area of responsibility, the AWACSs’ role is to patrol the air, providing friendly aircraft with early warning about possible threats and coordinating friendly forces in response to those suspected threats. Specifically, the AWACS is tasked with ensuring that everything that is within the airspace at any moment in time has been previously scheduled (according to an air tasking order) and facilitates the coordination of friendly force functions (e.g., mid-air refueling).

The next highest level of abstraction is the priorities and values of the system. This level represents more abstract functions, namely the situation independent values and priorities that must be adhered to in order to accomplish the functional purpose of the system. Priorities and values in the AWACS involve maintaining knowledge of activities within the area of responsibility. Specifically, priorities and values for the AWACS include establishing, updating, and disseminating tactical information; exercising control of friendly assets; and protecting friendly assets (i.e., platforms, sensors, and information systems).

The next level of abstraction delimits the general functions of the system that are the means whereby measurable priorities and values can be met. In the case of the AWACS, an important general function is detecting, tracking, and coordinating friendly assets. This involves continuously evaluating the tactical situation, communicating the tactical 'picture' to friendly parties, and implementing protective measures when necessary. The general functions of a complex system are supported by specific physical functions (the next level of abstraction). Physical functions are actual, specific physical process systems that accomplish a certain role (e.g., gathering data). The lowest level of the abstraction hierarchy is the physical form level. Physical forms are the entities or the most micro-level forms that support physical functionality (e.g., AWACS radar).

A part/whole decomposition is a specification of the levels of analysis an analyst wishes to delineate. For example, a complex system can be broken down into components and subcomponents. Thus, in terms of the AWACS, the category 'gathering data' can be broken down into storing and processing data and exchanging information.

Cognitive systems engineering principles highlight the importance of understanding the value, action, and information constraints of a control problem (i.e., work domain). Indeed, the abstraction hierarchy provides an excellent example of how to uncover the variety of a work domain so that appropriate control solutions can be anticipated to maintain stability. It should be clear that representing domain constraints is a necessary precondition for perceiving specific connections between values, actions, and information. However, although the abstraction hierarchy represents the control problem, it does not specify *how* agents develop control solutions to stabilize the system. In other words, the abstraction hierarchy reveals potential control problems but does not indicate specific control solutions – only possibilities for developing solutions. The next chapter discusses *how* agents develop control solutions through sensemaking. With an understanding of how, we can guide the design, support, and protection of safety-critical, complex socio-technical systems.

CHAPTER 3: FROM NOVICE TO EXPERT: THE EVOLUTION OF A HRO

Control problems that are characterized by unanticipated variability require flexible and adaptive control *solutions* (i.e., control solutions with sufficient variety). Organizations are successful at maintaining stability to the extent that they can eliminate a recognized discrepancy between what the organization wants to happen and what is happening. The role of developing an abstraction hierarchy is to uncover control demands in order to inform the development of 'transparent' representations (i.e., revealing work domain constraints) that allows agents to develop possible control solutions. However, an outline of the field of possibilities does not specify *how* control solutions develop and evolve. An understanding of how an organization learns behaviorally over time and from experience is needed to elucidate the control solution aspect. Specifically, understanding how an organization learns provides valuable insights into how it develops and employs specific control solutions to dynamic and complex control problems.

Continuous Organizational Learning

Organizational learning (i.e., developing control solutions) is important because it is the process whereby organizations adapt to complex and ever changing situations. If situations are relatively static and predictable, standards and plans can be effectively utilized in order to maintain system stability. However, when situations change and the future trajectory of system behavior is uncertain, agents must be capable of changing their behavior and beliefs about the work domain.

Organizational learning occurs when a system reflects on its experience and action, draws conclusions, and uses conclusions to guide behavior (Dewey, 1896; Mead, 1910; Weick, 1995). Learning is purposeful, in that it is directed at solving a meaningful control problem, i.e., something that obstructs progress toward an integral goal. Learning involves restructuring performance and acquiring new methods and skills (i.e., effortful adaptation; Ericson & Charness, 1994). Indeed, expert performance (i.e., consistently superior performance) is contingent upon effortful adaptation wherein agents adjust to the demands of emerging situations (Ericson & Charness, 1994). To the extent that problems or surprises consistently emerge through complex HROs, learning is *continuous* (i.e., control solutions are continuously being refined and adapted).

Continuous learning is a requirement for organizations that "operate under very trying conditions all the time and yet manage to have fewer than their fair share of accidents" (HROs; Weick & Sutcliffe, 2001). Thus, HROs must anticipate large problems from small disturbances and be capable of flexibly adapting to surprising situations (Weick & Sutcliffe, 2001). The following sections explore the process of organizational learning as developing, employing, and evaluating specific theories of action (i.e., control solutions) for dynamic and complex control problems.

Theories of Action

Strategies developed to address particular work demands are based on beliefs, derived from experience, about a system's constraints (Dewey, 1938; Rasmussen, 1994). As discussed in the previous chapter, understanding system constraints is a necessary precondition for perceiving specific connections between values, actions, and information. Through this understanding and experience with a work domain, alternatives and patterns for self-control emerge, resulting in specific control strategies.

Knowledge of a specific connection between an action and a consequence is defined as a belief, control solution, or *theory of action* (Argyris & Schon, 1985; see p.

34). Indeed, “from the perspective of the agent who holds the theory [of action], it is a theory of control” (Argyris & Schon, 1985; p. 81). Maintaining control of a complex and dynamic situation can be seen as experimenting, undergoing, establishing and referring to beliefs about the objects of experience and their consequences. The maintenance of theories of action and their influence on action persists unabated so long as stability is maintained. In other words, a validated control solution remains static until violated (i.e., proves inadequate).

Argyris and Schon’s (1985) *theories of action* provide a theoretical framework for understanding the development and modification of control solutions. Theories of action conceptualizes human agents as ‘designers of action’ that direct behavior to achieve intended consequences and monitor consequences to determine if they are meaningful (e.g., effective). According to the authors, agents “…make sense of their environment by constructing meaning to which they attend, and these constructions in turn guide action. In monitoring the effectiveness of action, they also monitor the suitability of their construction of the environment” (Argyris & Schon, 1985; p. 81). Thus, in Argyris and Schon’s (1985) terms, agents must develop simplified representations of the control problem and a small set of potential theories of action (i.e., hypotheses or control solutions based on control problem constraints) to maintain system stability.

When faced with an unanticipated situation, agents can change their prior beliefs about a situation by generating a small set of theories of action that might explain the surprise determine methods for system stabilization (Argyris & Schon, 1985; Klein, 1993; Peirce, 1908; Weick, 2005). The process of formulating an apparently valid theory of action in light of unanticipated variability and testing the viability of that theory of action through current conditions is called *abduction* (Peirce, 1908). The selection of a theory of action (i.e., hypothesis) and subsequent testing of that theory of action is described by Peirce (1908), who stated that there are two criteria for the generation and selection of hypotheses: 1) a hypothesis should be *explanatory* in that it should be generated with the intent to explain a surprising phenomenon, 2) a hypothesis should be *verifiable* - it should be testable by deducing possible predictions, and testing these predictions by means of induction. For instance, in the domain of combat air operations an AWACS WD discovers an unknown track on her situation display (see Chapter 2). The AWACS WD hypothesizes that the track is either an enemy aircraft, a friendly aircraft that was (inadvertently) not scheduled to be in the area, or an error in the radar sensor (e.g., noise). Each of the above hypotheses can explain the unknown track and can be verified by a variety of procedures. For example, the AWACS WD can consult the ATO to determine if it was previously scheduled; she can consult with the AOC to establish if any last minute friendly missions were scheduled; she can order a friendly fighter to engage in a fly-by to visually assess the nature of the unknown track.

Sensemaking

Abduction is the general foundation for the process of *sensemaking*, which has a strong literature base with research that focuses on organizations that exhibit a variety of levels of complexity (Leedom, 2001; Weick, 1979; 1995; 2005). Sensemaking is an ongoing process of creating plausible meaning in the flow of experience. Specifically, sensemaking involves retrospectively interpreting situations (*sense*) and prospectively enacting a potentially new configuration of the environment (*making*; Weick, 1995). Sensemaking explicitly occurs when the current state of the world is perceived to be different from the expected state of the world, namely when belief is broken (i.e., a surprise). New experiences are typically framed against expectations based on old experiences - otherwise, surprise has no meaning. The process of sensemaking is best described in terms of Piaget's concepts of *assimilation* and *accommodation* (Piaget, 1928). Assimilation imposes organization on new experience by incorporating it into the framework of previous experience. In other words, if a particular theory of action effectively stabilizes a system in light of a specific control demand, that theory of action will be utilized in similar future situations. However, when an existing experiential framework fails to effectively cope with unanticipated variability, the framework must be changed. Put differently, if a theory of action fails to stabilize a situation, it should be changed. Failure to change a theory of action (i.e., experiential framework) can lead to confirmation bias.

Confirmation bias. Learning and the development of successful theories of action are inhibited when agents discount new information that contradicts prior beliefs. Goh and Wiegmann (2001) provide an example of the effects of confirmation bias when they found that although severe changes in weather were directly relevant to safely flying an aircraft, some pilots did not consistently detect weather changes because they maintained the belief that their flight plan was safe. Ultimately, the pilots sought information that confirmed their belief that their flight plan was safe and discounted information to the contrary. Similarly, O'Brien and Ellsworth (1996) found that if a police officer believed that a person was likely to be a suspect (i.e., they match a description, are located in a high crime area, act strangely) the officer was likely to form a belief that the person was potentially dangerous. With this belief in mind, the officer tended to look for evidence to support their belief and ignore, avoid, or rationalize evidence that contradicted it. When the person appeared with an object in hand, it was interpreted as a gun (O'Brien & Ellsworth, 1996). This conclusion confirmed the initial belief that the suspect was dangerous. It should be clear from the above examples that unquestionable adherence to beliefs can lead to negative outcomes when coping with surprise. Learning in terms of successful and flexible theories of action result when underlying values and assumptions that distort understanding are questioned (Argyris & Schon, 1996).

Making sense. When a specific strategy does not successfully stabilize a system in light of uncertainty, innovative theories of action must be developed and deployed. This accommodation, or sense *making* reflects an adaptive change toward improved fitness (Piaget, 1928; Weick, 2005). Put another way, sensemaking represents the process of developing a better match between old theories of action and new experiences. For example, a homeowner notices a leak under the sink (i.e., control problem) that she believes is due to a loose pipe fitting that she prefers to tighten on her own (i.e., control solution). In this example, there are two aspects of the control solution or *theory-in-use* that are important to note: First, the homeowner *prefers* to fix the leak herself. Argyris and Schon (1985) define values and preferences that agents seek to satisfy as *governing variables*, which represent specific value constraints that guide beliefs and action. Second, Argyris and Schon define the homeowner's actions in terms of tightening the fitting as an *action strategy*. In other words, action strategies represent the specific control strategies afforded by constraints on action.

To continue with the above example, the homeowner manually tightens the loose pipe fitting, which stops the leak, thereby confirming her action strategy (feedback about the status of the leak represents constraints on information). Several months later, the homeowner again notices a leak under the sink. She engages in the pattern of action that relates to her previously confirmed theory of action and attempts to manually tighten the loose pipe fitting. However, tightening the loose pipe fitting (i.e., action strategy) does not appear to stop the leak. The homeowner decides to forcefully jiggle the pipe, which stops the leak. Argyris and Schon (1985) define utilizing a new action strategy (i.e., forcefully jiggling the pipe) in the service of the same governing variable (attempting to fix the pipe herself), *single-loop learning*. In other words, the homeowner assimilates the new action strategy into her existing experiential framework.

Alternatively, if forcefully jiggling the pipe does not stop the leak and cracks the pipe and causes a mild flood in the kitchen, the homeowner possibly will question her role in fixing the pipe and may decide to call the plumber. Argyris and Schon (1985) define this type of learning, whereby governing variables or values are questioned or modified and new action strategies developed, *double-loop learning*. Double-loop learning represents sensemaking, or the accommodation of a new experiential configuration of the environment. In other words, "single-loop learning is like a thermostat that learns when it is too hot or too cold and turns the heat on or off. The thermostat can perform this task because it can receive information (the temperature of the room) and take corrective action. *Double-loop* learning occurs when error is detected and corrected in ways that involve the modification of an organization's underlying norms, policies and objectives" (Argyris & Schon, 1978, p. 2-3).

During standard operations, strategies to cope with minor disturbances are assimilated into a pre-established belief system or framework through single-loop learning. In organizations wherein coordination is achieved through standardization or by plan, single-loop learning is sufficient – indeed, desired in order to maintain system stability. To be sure, system designers (or organizational executives) do not want agents to change the governing variables that support stable system functioning. For example, in a process control plant (e.g., nuclear power, chemical synthesis plant; systems with tight coupling and high dimensionality), operators are tasked with ensuring that specific physical processes are within some acceptable range (i.e., governing variables). Depending on action and information constraints, operators can utilize a variety of action strategies to keep process values within the range delimited by governing variables. However, altering governing variables can compromise the systems integrity. In other words, in process control, the governing variables are set by the constraints of the physical system (e.g., nuclear physics) and it is the operator's role to employee control solutions to ensure that physical performance stays within safe limits.

In systems characterized by uncertainty and unanticipated variability, wherein stability is maintained through mutual adjustment, both single-loop and double-loop learning are effective ways of making decisions about the design and implementation of action. To refer back to the earlier AWACS example (a system with loose coupling and high dimensionality), single-loop learning leads to incremental changes in the way WDs cope with anticipated situations. Thus, many AWACS situations require WDs to focus on tactics or specific action strategies implemented to stabilize expected or standard situations. When WDs detect an unknown track, they can rely on their ATO to determine if the track is a scheduled friendly aircraft. According to Air Force Doctrine, the ATO represents *the* detailed schedule of every event within an area of responsibility during a specified period of time. If an unknown track does not show up on the ATO as a scheduled event, the WD can suspect that the unknown track could have hostile intent. Double-checking with the air operations center (the developer of the ATO) can rule out most potential ATO errors. Additionally, the AWACS IFF system can reveal that the unknown track does not emit a 'friendly' signal. Consequently, based on the governing values of standard AWACS operations, the unknown track can be identified as hostile. However, what if the AWACS operator questions the suitability of the governing values in determining the status of the unknown track? What if the unknown track is NOT hostile? What if the aircraft's IFF signal and radio is not working properly? What if someone forgot to schedule some activity within the area of operations? What if the unknown track is a civilian aircraft that is flying outside of its original flight plan? Under these circumstances, WDs might examine the original way that they interpreted the unknown track and evaluate the values, beliefs, and assumptions that are leading them to frame the unknown track as hostile. Perhaps, the governing variables are insufficient for coping with this unanticipated situation. Thus, the AWACS WDs deviate from standard action strategies, avoid confirmation bias, and call in a fighter aircraft to conduct a fly-by to visually determine the intent of the unknown track.

Summary. All systems require agents, at the individual-, team-, and platform-level, to assimilate effective theories of action based on prior experience. However, systems characterized by surprise require agents to re-frame theories of action in order to accommodate unanticipated situations. In other words, in order to cope with complex and ambiguous situations, organizations must engage in both single-loop learning and double-loop learning (i.e., sensemaking). When confronted with a surprising situation, agents formulate and select a theory of action that can account for the unanticipated event. These theories of action are 'tested' within action constraints and their utility determined through constraints on information. If a theory of action stabilizes the system (i.e., satisfies the control problem), it will become a tentative part of the belief system to be utilized again in similar situations.

Developing Expertise

Extended experience through a specific work domain, wherein an agent has the opportunity to maintain stability through the development and employment of a multitude of control strategies leads to expertise (Ericson & Charness, 1994). Like novices, experts engage in sensemaking when they encounter unanticipated situations. However, unlike novices, experts focus on the relevant features of a specific control problem. Therefore, experts are better able than novices to monitor the suitability of their construction of the environment, which guides action (Argyris & Schon, 1985). The following sections explain the development of expertise through extended experience through a specific work domain.

Through iterative cycles, agents make sense of challenging situations by integrating theories of action that lead to construction of new knowledge (i.e., beliefs). By restructuring performance, acquiring new methods and skills through experience with a work domain, and consistently maintaining stability, organizations achieve expert performance (Ericson & Charness, 1994). In other words, experts acquire stability by 'extended adaptation' to the specific value, action, and information constraints of the work domain (Ericson & Charness, 1994). With extended experience through a work domain, agents are able to recognize familiar situations, anticipate potential control problems, and coordinate adaptive responses to maintain stability. Indeed, Ericson and Charness state that "in the perceptual environment…expert performance is continuous and changing, and experts must be able to recognize if and when a particular action is required. Most important, it is possible for the expert to analyze the current situation and thereby anticipate future events" (1994, p. 736). Flach and colleagues (1990) define the abovementioned process of discovering the significance of situations, *attunement*.

Flach (1990) argues that expertise is contingent upon the degree of coupling between an agent(s) and a work domain. Thus, an expert's interpretation of a particular situation highly corresponds to the significance of that situation relative to a specific work domain (Flach, 1990). In other words, experts recognize or *attune to* meaningful patterns of information within a work domain that are directly related to domain functionality (e.g., threats, opportunities; see Figure 3.1). With continued experience through a specific work domain, experts become attuned to large meaningful patterns of information in the work domain; perform at a faster pace and in a relatively error-free way compared with novices; and make sense of control problems (e.g., surprise) in a more principled way than novices (Glasser & Chi, 1988; cited in Flach, 1990).

	AWARENESS	
SITUATION	**Attuned**	**Unattuned**
Significant	**FUNCTIONAL (Informative)**	**NONFUNCTIONAL (Noninformative)**
Not significant	**DYSFUNCTIONAL (Misinformative)**	**AFUNCTIONAL (Uninformative)**

Figure 3.1. Correspondence between situation and awareness (Flach, et al., 1990).

Flach and colleagues (1990) describe the development of expertise in the context of the Figure 3.1:

> *A [expert] is one who can tune into task relevant structures and who can tune out task irrelevant structures. The development of [expertise] can be conceived of as a migration of information within the matrix . . . such that nonfunctional structures become functional and dysfunctional structures become afunctional. [Experts attuned to] relevant event structures to which the novice is unattuned. [Learning involves] extinguishing attention to irrelevant structure (make dysfunctional structure afunctional). Attending to irrelevant structure may, at worse, lead to divergence from the task objectives (errors) and at best constitutes an inefficient use of limited attentional resources* (p. 329).

Referring back to voice loops within the domain of space shuttle mission control (see Chapter 2) experts are better able to attune to significant patterns within the flow of active communication than novices. Extensive experience with listening in on voice loops affords operators the opportunity to discover invariant patterns of communication that correspond to properties of space shuttle mission control. Therefore, expert operators quickly attune to situational patterns that are significant with regard to the functional goals of mission control (Gibson, 1969, cited in Flach, 1990). Specifically, from communication patterns through voice loops, operators are able to recognize when there are problems within adjacent subsystems, how a problem might be emerging due another operator's behavior, when to interrupt other operators to ask significant questions, and how deviations in the typical flow of voice loop communication relate to the overall health of mission control.

To reiterate an important point, expertise is contingent upon the degree of coupling between agents – at the individual, team, or platform-level - and a work domain. Thus, a "team's situation awareness or the team's understanding of a complex and dynamic situation at any one point in time" plays a critical role in team performance (Cooke, et al., 2003). Expertise, or consistently superior performance is attained by attuning to significant situational patterns of information that have been discovered through experience with a dynamic work domain.

Summary

In the above sections, it was argued that maintaining the stability of complex and dynamic systems, such as AWACS, is predicated on continuous organizational learning. Indeed, understanding how agents develop theories of action for dynamic and complex control problems is an important first step in designing, supporting, and protecting complex socio-technical systems. Learning was explained from the perspective of theories of action, whereby control solutions are either based on previous experiential frameworks (i.e., single-loop learning; assimilation) or are based on accommodating new hypotheses based on new experiential frameworks (i.e., double-loop learning; sensemaking). The next chapter elaborates on how the continuous organizational learning processes that occur through complex socio-technical systems, such as the AWACS, can be scientifically explored. Additionally, the methodology employed for a specific study is discussed.

CHAPTER 4: SYNTHETIC TASK ENVIRONMENTS: MANAGING COMPLEXITY IN THE LABORATORY

To cope with complex control problems, agents must be capable of understanding constraints on values (i.e., purpose), action (i.e., what agents can *do*), and information (feedback that enables controlled action). Specifically, agents jointly construct understanding of value, action, and information constraints through mutually adjusting to each other and to dynamic situations. In other words, agents jointly develop theories of action through the ongoing process of sensemaking. The occurrence and importance of this process increases in complex systems that are characterized by loose coupling and high dimensionality, such as HROs, where situational uncertainty and ambiguity are high.

Unfortunately, questions related to how one scientifically studies this process have not been addressed. In other words, how can a scientist conduct empirical research on complex domains to better understand how agents learn domain constraints and, in turn, jointly develop effective control solutions?

It is extraordinarily difficult to conduct empirical research through many complex domains, such as AWACS battle management. Indeed, due to the hazards of conducing research through a 'live' domain and the multiple levels of organizational performance inherent to complex domains, scientists tend to reduce and simplify experiential phenomena in order to allow sufficient experimental control. Although reducing and simplifying experiential phenomena affords experimental control, it also neglects dynamic and emergent behavior and multi-level performance characteristics of complex systems. On the other hand, conducting empirical research through complex natural work domains is not feasible (e.g,. due to safety, cost). Synthetic task environments (i.e., STEs; also known as microworld environments) bridge the gap between naturalistic empiricism and experimental reductionism by offering a rich (i.e., meaningful) representation of a complex work domain and sufficient experimental control.

The following chapter will explore science from the 'classical' reductionistic point of view and explain the limitations of its premises in regard to studying complex systems. Due to these limitations, this chapter advocates an alternative, 'science of complexity' when attempting to understand behavior through complex systems. STEs are discussed as a pragmatic tool for reflecting the meaningful aspects and multiple performance dimensions of the AWACS air battle management domain, uncovered by cognitive work analyses, within the relative control inherent to a laboratory.

Supplementing 'Classical' Science with a Science of Complexity

Contemporary organizational theorists – and, scientists in general, take a limited view of the world of natural phenomena. In Chapter 1, Perrow's complexity space was transformed into a representation of what we consider to be the meaningful dimensions of complexity (see Figure 2.1). From this new vantage point, it can be seen that HROs fall outside the purview of NAT (see Figure 4.1). In general, it can be seen that many complex phenomena fall outside the purview of 'classical' science. To be sure, NAT and many forms of contemporary science take a more 'classical' approach to natural phenomena. Thus, systems with well defined and relatively static natural constraints are most frequently scientifically explored. This preference for systems that exhibit characteristically few degrees of freedom and tight coupling is probably due to the ease and efficiency of using classical scientific techniques, such as controlled laboratory experiment. However, when systems are open, have many constraints (i.e., high dimensionality) and are relatively loosely coupled, ‘classical’ techniques for understanding natural phenomena can be too simplistic to account for complex behavior.

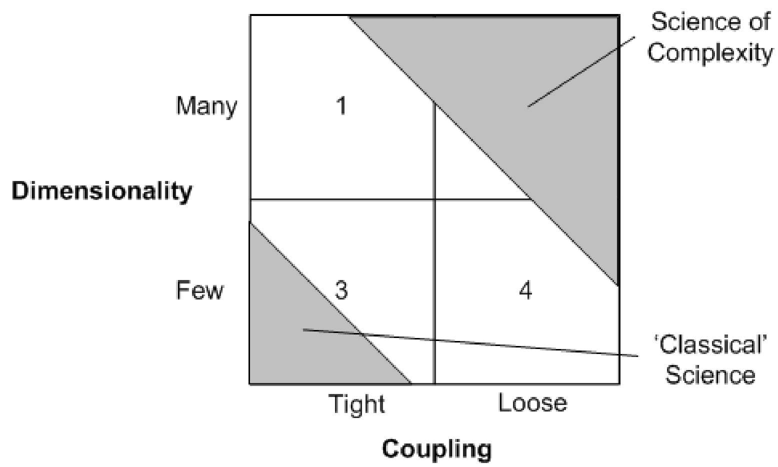


Figure 4.1. Traditional science versus a science of complexity.

‘Classical’ Science vs. Science of Complexity

The classic paradigm for studying the complexities of organization is based on Newton's methods of understanding the universe. Newton's universe was a linear, closed set of events governed by cause and effect and the conservation of matter and energy. Matter was considered to be composed of a finite number of indivisible particles. Energy was thought to be a characteristic of matter. The goal of physicists was to gather enough facts so that they could predict any event with absolute certainty. Edward Lorenz found that in fluid systems like the atmosphere (i.e., systems with variables that are completely interconnected), even tiny changes in the modeling of such systems produces what is known as a 'butterfly effect' – that is, a divergence in behavior that is disproportional to the size of the initial difference. Thus Lorenz (1963) found that there was 'sensitivity to initial conditions'.

Coming to the same conclusion as Lorenz, some scientists have reasoned that the nervous system dynamically interacts with enough inputs of complexity to be considered a chaotic, unpredictable system (Mandlebrot, 1982). What these scientists argue is that cause and effect are part of a dynamic interplay that results in phenomenon that science may not be able to dissect with a reductionist methodology. The idealization of isolation (i.e., reduction) ignores the interaction between object and environment, the interaction between particle and space. To be sure, 'classical' science attempts to force open-systems into a closed-system space. However, considering nature as a closed system constrains the phenomenon: there are no closed systems in nature. Thus, any description of organization in terms of causes that are isolated from the system will be incomplete (see Kurt Godel's theorem of incompleteness, 1979).

Circular causation. It is difficult to discern cause from effect in systems with loose coupling and high dimensionality. Indeed, in such systems there is a circular dynamic between cause and effect. Thus, for example, a behavioral motor response determines stimulus just as truly as a sensory stimulus determines movement (e.g., Dewey, 1896); action creates interesting goals at the same time goals justify action (e.g., March, 1971; Weick, 1995); agents affect technology and culture just as technology and culture affects agents (e.g., Hutchins, 1995). Attempting to reduce whole situations into isolated elements is a dangerous affair; making causal attributions about those isolated elements is even more dangerous. To be sure, through complex biological organization, Nicolis and Prigogine (1989) make clear that an apparent cause is usually a result of some former cause, and effects tend to affect cause; a multiplicity of interaction and emergence typically qualifies post hoc discovery of a phenomenon. Certainly, in order for sense to be made of organization, phenomena of interest must be explored in context.

Context matters. John Dewey (1938; p. 72) states that "What is designated by the word 'situation' is not a single object or event or set of objects and events. For we never experience nor form judgments about objects and events in isolation, but only in connection with a contextual whole [i.e., a situation]." Indeed, scientists have continuously focused attention on abstract pieces or static moments of complex processes. Dewey reminds us of the fallacy of taking a singular object or event for the subject-matter of analysis, for "in actual experience, there is never any such isolated singular object or event; an object or event is always a special part, phase, or aspect, of an environing experienced world- a situation" (1938; p. 67). Thus, observation of an object or event occurs in an experiential 'field' that defines and constrains the object or event. Any qualification of the object or event must be made within the contextual frame of reference. Hence, understanding complex systems requires determining the dynamic, meaningful constraints on action (Hutchins, 1995; see also Cybernetic theory; Weiner, 1948; 1967).

Bridging the Gap: Synthetic Task Environments

Scientific research exploring complex systems through reductionism neglects meaningful dimensions of complex systems, whereas empirically exploring a complex natural domain is not feasible. Synthetic environments based on in-depth analyses of a complex domain provide a meaningful method of bridging the gap between these disconnected paradigms (see Figure 4.2).

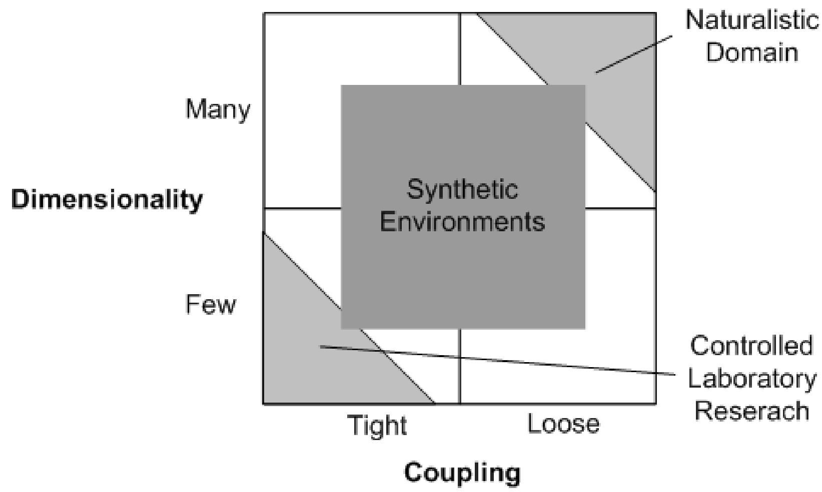


Figure 4.2. Bridging the gap between the naturalistic domain and traditional laboratory research.

Synthetic environments. Synthetic environments provide a medium-fidelity environment through which an experimenter can represent the essential relations and characteristics of a domain (i.e., the complexity, dynamics, and transparency) while maintaining a moderate level of experimental control (see Brehmer & Dorner, 1993, for a discussion on Synthetic Task Environments and their use). As mentioned above, complexity is reflected in the degree of coupling and dimensionality of a work domain. Loosely coupled, high dimensional systems exhibit greater complexity than tightly coupled, low dimensional systems. Synthetic environments allow a scientist to model the loosely (or, tightly) coupled components according to varying degrees of dimensionality. The dynamics (i.e., continuous change within a system) of a situation are revealed when an action effects all subsequent actions – as in the ‘butterfly effect’ seen by Lorenz in his seminal work on complexity in weather systems. Thus dynamics are present when a system has ‘memory’ and can ‘remember’ what has happened through it. Synthetic task environment dynamics are a function of both the state of the synthetic environment (as modified by earlier actions) and the current action. Because the environment is dynamic, agents must respond to changing situations.

The relative transparency or opaqueness of a system is the degree agents can ‘see’ or understand the various and changing constraints of a domain. For example, firefighting involves developing strategies based on an understanding of various constraints on value (e.g., extinguishing fires and saving lives), action (e.g., breaking through walls, dowsing with water), and information (e.g., radio transmitters, infra-red goggles) unique to firefighting that must be understood in order for agents to control the system. However, removed from the danger inherent in firefighting environments, these same constraints can be represented in a STE, allowing for an empirical examination of transparency. As agents transact with synthetic environmental situations, they can discover and jointly construct control solutions for complex fire-extinguishing problems such as backdraft. Thus, the underlying processes can be examined in a manageable and safe environment.

In order to develop a synthetic representation of a complex environment one must understand the system’s constraints. One strategy for modeling and understanding the functional constraints of a complex work domain is conducting a work domain analysis (see Rasmussen, Pejtersen & Goodstein, 1994; Vicente, 1999). Work domain analysis uncovers the goals and constraints, the *potential relationships* among goals, functions and processes, the criteria available for allocation of roles to individual agents, and the coordination needed….” (Rasmussen, 1991).

Cognitive Work Analysis. To gain insight into the dimensionality of a work domain, it is necessary to explore and analyze the field of work (i.e., constraints on value, action, and information) in a natural setting (i.e., where the phenomena of interest occur). Thus, cognitive work analysis (i.e., CWA) represents an approach to understanding work domains by evaluating existing system behavior in context (see Chapter 2). Cognitive work analyses focus on the functional purpose(s) of a system or work domain, the general and specific rules and principles that guide purposeful system behavior, and the physical functions and properties that help realize overall systemic functionality (Rasmussen et. al., 1986).

Cognitive work analyses have been used in a variety of systems to gain a better understanding of the field of work (e.g., library search - Pejtersen, 1989; nuclear power plant safety - Rasmussen, et al., 1994; process control -Vicente, 1999). Specifically, and of relevance to this work, several CWAs have been performed in the AWACS domain (Fahey, Rowe, Dunlop, & deBoom, 2001; Hess, MacMillan, Serfaty, & Elliot, 1999; Klinger, Andriole, Militello, Adelman, & Klein, 1994; Means & Burns, 2005; Schiflett, Elliot, & Cardenas, 2000). These work analyses elaborate, at a fine level of detail, AWACS BMC2 fields of work – hence, helping to answer questions pertaining to what to study and what metrics matter. Further, from these work analyses, it is possible to *re*construct or *re*present the fundamental functional, ideological, and physical dimensions of the AWACS battle management work domain – thus, helping to answer questions pertaining to who and what we study and what types of scientific tools we employ.

From a scientific perspective, the processes associated with discovering and developing solutions to stabilize complex problems are as important as the emergent situational outcomes that result. Processes represent the strategies and behavioral patterns that are continuously adapting to changing demands. Thus, processes are capturing organizational dynamics across events and situations. On the other hand, outcomes represent a ‘snapshot’ of what was achieved in regard to specific organizational values. Ultimately, performance through complex domains is characterized by both process and outcome-related dimensions.

Processes vs. outcomes. Systems can be viewed from a process or outcome orientation. Processes represent the ‘operators’, ‘actions’, or ‘means’ that cause a sequence of changes in the properties of a system. Processes are the means for transforming or moving from one system state to another. Outcomes represent the ‘state’ dimensions (i.e., the changes or consequences resulting from a process, operation, or action). Therefore, a trajectory through a state space reflects an outcome wherein the actions that ‘drive’ the motion through the state space are the processes. Thus measures of performance can be categorized as indexing either processes or outcomes. Process measures reflect the sensemaking and communication processes that bring together the experience, skills, resources, and technology of various agents to execute a mission or plan. Outcome measures address the actual results achieved and the impact of a team completing (or not completing) a specific mission. Both process and outcome measures can be collected through synthetic environments. Communication and sensemaking processes can be examined over time and specific outcome measures can be tabulated from performance relative to mission requirements and goals.

Synthetic environments allow an experimenter to measure both process and outcome from multiple levels of abstraction. Additionally, performance relationships between levels of abstraction can be explored empirically. Higher levels of abstraction represent the more holistic or emergent properties of a system. Alternatively, lower levels of abstraction represent the particulate or component elements that interact/transact to form the emergent, holistic properties of a system. For example, in thermodynamics, phases are emergent phenomena produced by the self-organization of a large number of particles. Phase transitions are the sudden physical transformation of one phase to another (e.g., liquid to gaseous phase) due to a change in temperature. Thus as temperature changes past a critical point in a thermodynamic system, there are qualitative changes in the patterns among particulates. This relates directly to performance in complex domains: the emergent behavior of the organization (i.e., mission success) is analogous to temperature and the micro-behavior of agents represents particulates. As mission success changes (e.g., increases) one might expect to see qualitative changes in patterns among the particulates (e.g., strategy patterns) or vice versa, changes in patterns of behavior at the micro-level may lead to enhanced mission success.

Air Battle Management

Air Battle Management is a complex domain that can be represented in a STE, affording the examination of the research question: what is the relationship between phase changes in strategy and the level of mission success. Air Battle Management entails effecting command and control (C2) of assigned forces by planning, organizing, and directing operations. Air Battle Managers, also known as Weapons Directors (WDs), provide friendly forces with a 'big picture' of the battle-space; assisting in finding, identifying, and destroying enemy targets, keeping track of friendly assets, and coordinating air refueling.

Air Battle Management functions are accomplished at the operational level (i.e., the planning, conducting, and sustaining of large units to obtain strategic goals within a theater) through Air Operations Centers (AOC). The AOC is the centralized operational facility that plans, directs, and controls deployed air assets (Air Operations Center Standard Operating Procedure; Twelfth Air Force Air Force Forces). The Combat Plans Division is the AOC element responsible for building the air campaign plan and the daily Air Tasking Order (ATO), which is the published order that directs all air missions (Air Operations Center Standard Operating Procedures).

Air Battle Management functions are accomplished at the tactical level (i.e., combat operations taken to achieve specific objectives) through the USAF E-3 Airborne Warning and Control System (AWACS), the E-8 Joint Surveillance Target Attack Radar (STARS), the USN E2C Hawkeye (see Armistead [2002] and Williams [1997] for more information on airborne platforms), and a variety of ground-based Control and Reporting Centers (CRC). At the tactical level, functionality is contingent upon sensor capabilities: AWACS and JSTARS' radar and computer subsystems can gather and present expansive and detailed battle-space information for air-to-air and air-to-surface battle management; USN E2C Hawkeye is a carrier-based system with similar air-to-surface and air-to-air sensor capability for maritime tactical scenarios; and CRCs are land based, short-range systems responsible for tactical air control within their area of responsibility (AOR).

Despite the variety of battle management platforms, Weapons Directors (WDs; i.e., Air Battle Managers) perform analogous tasks, under similar conditions, with comparable displays and controls (Knott et al., 2007). Thus WDs are required to monitor a multiplicity of simultaneous communications channels under conditions of moderate to high ambient cabin noise while performing several visual and manual tasks (Bolia et al., 2005). Additionally, said tasks are performed as part of an integrated *team*. The latter requirement is significant because it emphasizes the importance of collaboration and coordination for the achievement of tactical and operational goals (see Chapter 3; Knott et al., 2007).

Weapons Directors working through the AWACS battle management domain must cope with agent and environmental interdependencies in order to successfully stabilize the battlespace situation. The following section describes the AWACS battle management domain (based on results of cognitive work analyses; Fahey, Rowe, Dunlop, & deBoom, 2001; Hess, MacMillan, Serfaty, & Elliot, 1999; Klinger, Andriole, Militello, Adelman, & Klein, 1994; Means & Burns, 2005; Schiflett, Elliot, & Cardenas, 2000) and how, by utilizing synthetic task environments, scientists can explore how agents jointly learn domain constraints and develop successful control solutions relative to complex control problems.

AWACS Battle Management

> The [Weapons Director] position can be likened to that of an Air Traffic Controller in the sky, with some important differences: commercial aircraft seldom shoot at one another, the Air Traffic Controller never needs to monitor an airborne track in order to determine intent; Air Traffic Controllers are seldom in danger of being shot down (they are not flying in the sky with the aircraft they are controlling); and they do not need to worry about rules of engagement. (Klinger, Andriole, Militello, Adelman, & Klein, 1994, p. 3)

The AWACS provides unprecedented aerial surveillance and battle management capabilities for the United States Air Force. Specifically, the AWACS can detect and track hostile aircraft over all terrain, identify static and mobile ground targets, and can control friendly aircraft in the same airspace during complex, dynamic, and time-sensitive situations (Boeing Corporation, 2007). The ‘heart and soul’ of the AWACS is a four to six member Weapons Director (WD) team. As Klinger and colleagues (1994) illustrate in the above quote, the AWACS WD can be equated to a military, airborne, air-traffic-controller that must work through an active battle-space according to a prescribed Air Tasking Order.

The AWACS WD team typically consists of three or more WDs that direct friendly assets, and one Senior Director (SD) that essentially performs as a WD team leader; often, the SD is the ranking officer. The WDs workload is divided either geographically or functionally. Thus each WD is assigned either a geographical region within the AWACSs' area of responsibility (AOR) or, more customarily, each WD is assigned a primary role or responsibility within the AOR. The standard functional division of labor among the WDs consists of a Tanker WD (i.e., primarily responsible for airborne tankers and coordinating re-fueling), a AOR WD (i.e, primarily responsible for the assigned airspace: coordinating fighters, identifying enemy targets, protecting friendly assets), and a Check-in WD (i.e., primarily responsible for 'checking' assets into the AOR and 'passing' them over to the AOR WD). Although, primary roles are assigned to each WD, all WDs receive the same training and are responsible for performing all roles depending on the situation. Thus AWACS WD functional roles are transferable; a feature that benefits the WD team during complex, dynamic, and time-sensitive situations (Schifflett, Elliot, & Cardenas, 2000).

The AWACS WD team assumes a command and control role for U.S. military forces. In other words, the WD team is responsible for accomplishing a variety of functions (i.e., allocating sensors, fighters, bombers, tankers, and assigning weapons and systems) in order to achieve desired operational effects (Means & Burns, 2005). AWACS teams fulfill this command and control role by interdependently tracking and coordinating tactical action in accordance with overall strategic goals and procedures over an extended period of time (Schiflett, Elliot, & Cardenas, 2000). Thus *teamwork*, or effectively managing interdependencies, is a fundamental function enacted by AWACS WD teams.

A *team* is defined as "…a distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/object/mission, who have each been assigned specific roles or functions to perform, and have a limited life span of membership" (Salas, Dickinson, Converse, & Tannenbaum, 1992; p. 4). Teamwork, or the adaptive *management* of dynamic interdependencies, depends on the degree to which team members must jointly manage value, action, and information constraints through unanticipated situations (i.e., environmental variability) and the extent to which agents within the team must manage agent interdependencies (Thompson, 1967).

An important aspect of a team, as defined above, is the notion of a set of dynamically interdependent agents acting adaptively *toward a shared goal or objective*. In addition to team action reflecting open-system characteristics in terms of coping with unanticipated environmental variability, team actions are expected to reflect closed-system characteristics in terms of goal directed behavior – to be rational and sensible. Rationality in an open-system is continuously challenged by 'external' *and* 'internal' uncertainties (i.e., distinctions within an ontologically holistic ecology). In other words, in open-systems, such as AWACS BMC2, there is an expectation of a certain degree of rationality, in terms of goals and decision-making that is continuously challenged by 'internal' and 'external' uncertainties. 'External' uncertainty is instantiated by a lack of value, action, and information constraint understanding based on an environments interrelationship with team action, whereas ‘internal’ uncertainty is instantiated by the interdependence of agents within the team.

To reiterate what was stated above, studying teams that work through complex, open-system domains such as AWACS BMC2 precludes the use of closed-system methods (e.g., controlled laboratory experiment) that preclude any sort of uncertainty or contingency. However, often it is not feasible to study AWACS BMC2 teams *in situ*. Synthetic task environments bridge the methodological gap, enabling scientists to trade off some degree of realism for experimental control without forcing phenomena into a completely closed-system. Thus, the present research examined AWACS BMC2 teams in action by developing a STE with domain relevant performance metrics based on the AWACS domain’s functional constraints (i.e., value, action, and information constraints), as delineated by several cognitive work analyses (Fahey, Rowe, Dunlop, & deBoom, 2001; Hess, MacMillan, Serfaty, & Elliot, 1999; Klinger, Andriole, Militello, Adelman, & Klein, 1994; Means & Burns, 2005; Schiflett, Elliot, & Cardenas, 2000).

AWACS STE: METHOD

Experimental Task

The Distributed Dynamic Decision-making (DDD; see Appendix A for screenshot of DDD) system developed by Aptima (http://dddweb.aptima.com) was used to develop STE scenarios based on the above mentioned analyses of the AWACS WD work domain. Once developed, the scenarios were reviewed for task, role, and mission realism by a subject matter expert (a former AWACS WD and SD).

Scenarios. Air battle management scenarios were developed for this experiment and are designed to require a team of three Weapons Directors (WDs), a Sensor Operator (SO), and a Senior Director (SD) to coordinate to sustain a pre-emptive strike. Weapons Directors coordinate operations (i.e., intercept threats and re-supply assets as needed) through communication, sharing of fighter and bomber assets, and allocating tanker assets and sensor information from unmanned areal vehicles (UAV). The scenarios were presented to WDs via the DDD tactical display (see Figure 4.3), which represented the area of operations with friendly assets and enemy targets shown as unique symbols. The tactical display afforded a real-time representation of the battle space from which WDs were able to monitor and direct simulated air operations.

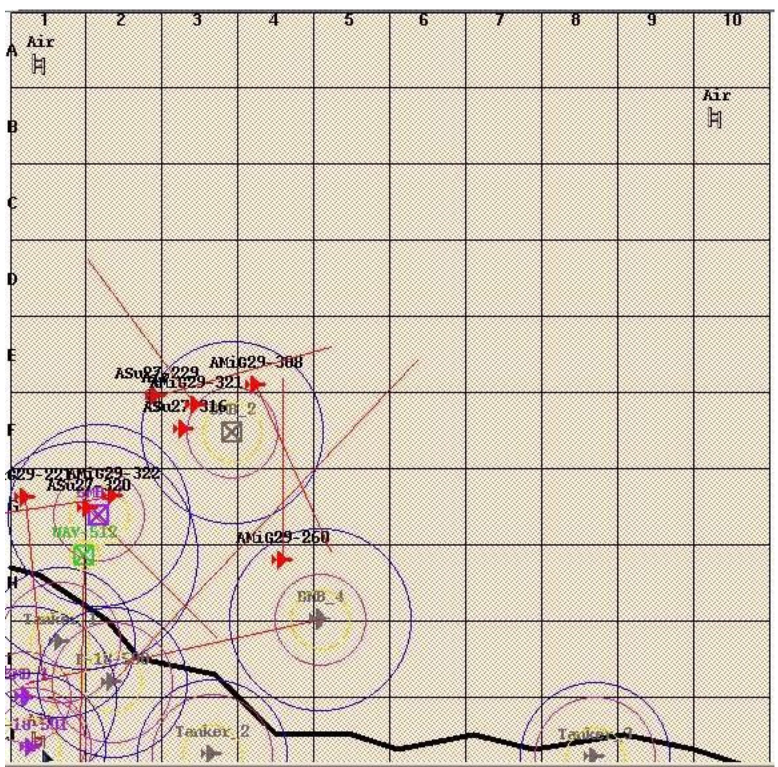


Figure 4.3. DDD tactical display representing a pre-emptive strike scenario within the AWACS area of responsibility (AOR).

The tactical display represents a specific area of responsibility (AOR) that contains all friendly and enemy assets/targets. The symbols represent assets that are labeled according to their platform type (e.g., F-18) and call-sign (e.g., BMB-2). There are three tanker aircraft for unlimited aerial refueling and re-arming of designated fighter and bomber assets; twelve fighter aircraft equipped with four air-air missiles, one air-ground bomb, and a random quantity of fuel; twelve bombers equipped with four air-ground bombs and a random quantity of fuel; and eight UAVs equipped with unlimited fuel.

Each 15 minute mission scenario is based explicitly on an air tasking order (ATO): all mission requirements and target priorities are delineated in the ATO (see Appendix B for example of ATO). Mission scenarios begin with an ATO and an intelligence briefing (see Appendix C) that graphically indicates possible locations of enemy targets. Mission scenarios contain several (occasionally mobile) enemy ground targets and mobile enemy air forces that follow random trajectories within an AOR that remains the same for all scenarios. Enemy forces have the ability to attack and destroy all friendly assets (i.e., fighters, bombers, tankers, and UAVs). Each mission scenario concludes with a de-briefing that includes individually administered surveys and jointly administered surveys, mediated by the SD (see Appendix D).

The experiment took place in a 9.75 m X 6.5 m room with three Weapons Directors (WDs) on one side of the room, a Sensor Operator (SO) on the other side, facing the opposite direction, and a Senior Director (SD) in the middle of the room. Each operator had a 17-inch flat-panel display that presented the tactical display, the DRAW whiteboard tool for visual communication, and Microsoft Instant Messenger for text messaging. ModIOS® Voice Communicator was used for simulated network radio communication. Voice and chat-based communications provided linguistic information whereas the whiteboard technology provided visual/pictorial information. The virtual whiteboard transparently overlaid the tactical display and provided operators with a 'shared whiteboard' whereby each member draws or writes in a shared space. The edited 'snapshots' of operators' visual interface were virtually shared in real-time with other team members. Operators were allowed to choose their method of communication (i.e., radio, chat, whiteboard).

Team composition and responsibilities. Each team is composed of three WDs, one SD, and one SO. The WD roles are divided into a set of primary, albeit transferable, responsibilities. The *Check-in WD* is primarily responsible for launching all aircraft from an airbase outside of the AOR and transferring those 'checked-in' friendly aircraft to the Area of Responsibility WD (*AOR WD*) and the *SO*. The *AOR WD* is primarily responsible for what goes on in the AOR: enemy targeting, fighter assets, and bomber assets. The third WD, the *Tanker WD*, is primarily responsible for coordinating re-fueling and restocking all friendly assets and is also responsible for protecting high value assets (i.e., Unmanned Aerial Vehicles; UAVs). Each of the WDs' responsibilities are transferable. For example, the *AOR WD* can transfer a bomber to the *Tanker WD*, who can then be responsible for bombing a ground target. The *WD*s and the *SO* communicate over one communication channel.

The *SO* is positioned separately from the *WD*s, but uses the *WD*s communication channel. The *SO* is responsible for controlling UAVs in order to detect the coordinates of enemy ground targets (that WDs can not detect) within the AOR. Additionally, the *SO* coordinates with WDs to extinguish all ground targets: a primary rule of engagement is that both *SO* and *WD* must maintain visual contact with an enemy target in order to attack it.

The *SD* is the officer in charge of the AWACS team. It is the *SD*s responsibility to coordinate mission de-briefings after each scenario was completed. Also, the SD provides supervisory support to *WD*s during specific control conditions.

The tactical displays for all operators provide a global picture of the battle space and friendly assets. However, WDs are able to see enemy aircraft and ground targets only when they come within the limited range of their platform's sensors. Specifically, WDs can see air targets when they come within the sensor rings of their asset and can only see ground targets when they are nearly on top of them. Additionally, WDs cannot see what other operators see. The SD, on the other hand, sees what all WDs see. The SO can see ground targets within the sensor rings of the UAV, however, cannot see any enemy aircraft. Thus, both the WDs and SO have limited awareness of the tactical picture and must rely on each other to accomplish mission objectives. In particular, WDs must provide SOs with information concerning mobile enemy aircraft around UAVs and the SOs must provide WDs with information concerning the location of ground targets throughout the AOR.

Participants. Two teams of five participated in the experiment, with the same confederate participating on both teams, resulting in a total of nine individuals (M age = 28; 6 male). Tables 6 and 7 represent the biographical composition of Teams 1 and 3. In addition to the noted characteristics, members on both teams were personally acquainted with each other (i.e., members of the same graduate school cohort).

Table 4.1

Team 1 Subject Biographical Data

Position	Education	Gender	Age	Military Experience	Hours Gaming Per Week	Gaming Enjoyment
Tanker WD	Graduate School	Male	28	5 years	1-10	4
AOR WD	Undergraduate	Male	20	1 year	1-10	7
Checkin WD	Graduate School	Female	39	12 years	1-10	4
SO	Graduate School	Male	23	0 years	1-10	6
SD	Graduate School	Female	29	0 years	0	3

Table 4.2

Team 2 Subject Biographical Data

Position	Education	Gender	Age	Military Experience	Hours Gaming Per Week	Gaming Enjoyment
Tanker WD	High School	Male	22	4 years	1-10	7
AOR WD	Undergraduate	Male	27	0 years	1-10	6
Checkin WD	Graduate School	Female	42	0 years	0	3
SO	Graduate School	Male	26	0 years	1-10	5
SD	Graduate School	Female	29	0	0	3

Procedure

Prior to the experiment, all participants completed a two day training program that consisted of a two hour PowerPoint training module and six hours experience engaging in STE mission scenarios (approximately 6 hours) that were unrelated to experimental mission scenarios. Participants were trained on the STE, the radio software, DRAW whiteboard tool, and chat. Participants were also trained on the specific objectives and rules of the mission and were instructed that the performance of the team would be measured for each trial based on how well they met their objectives and followed the rules. The trainer informed participants that the purpose of the study was to evaluate how teams work together and that they would be playing a computer game that required teamwork to meet the game's objectives. Training concluded with a quiz that all subjects were required to pass with complete accuracy (i.e., 100 percent correct). Upon successful completion of training, subjects selected their team role (i.e., AOR WD; Checkin WD; Tanker WD; SO), which they were to maintain across all STE mission scenarios.

Upon completing training, participants returned over the course of three months for experimental sessions. Each experimental session consisted of approximately eight trials. As mentioned above, after each trial, participants completed several subjective instruments designed to assess individual and team beliefs. Participants were given one 10-minute rest period after they had completed four trials. All major simulation events (e.g., the occurrence and outcome of attacks, refuelling events, etc.) were recorded in data logs for later analysis. In addition, video, voice, and chat communications were recorded.

Manipulation of Control Structure

Control structure was manipulated: half of all mission trials were executed in a centralized control structure (the other half were decentralized; trials were counter-balanced). Centralization entailed all WDs requesting permission to commit all acts through the SD (see Appendix E for figure of team layout and communication loop). Under these conditions, the SD had the ultimate say in whether a WD engaged an enemy fighter, engaged a ground targets, launched or transferred assets, or returned an asset to base. During decentralized control conditions, WDs had the authority to commit all acts without requesting permission from the SD.

A-Typical Mission Scenario

Both teams performed through fifty trials that were divided into five blocks of ten trials each. During the fifth, sixth, or seventh trial of each block, both teams experienced a non-typical mission scenario that consisted of enemy targets unfamiliar to participants, such as mobile tanks, soldiers, helicopters, or trucks. The purpose of these trials was to observe team behavior during particularly surprising mission scenarios.

AWACS WD Team Performance

As mentioned above, the multi-dimensional nature of performance within complex domains is represented by process and outcome-related metrics. To reiterate, processes are the means for transforming or moving from one system state to another, whereas outcomes represent changes or consequences resulting from processes.

Quantitative outcome-related metrics. Outcome performance on the DDD AWACS battle management task is operationally defined using four quantitative (dependent) measures:

1. *Number of ground targets destroyed*: A measure of the number of ground targets successfully destroyed by the AWACS team/individual. The ground targets are an element of the ATO and represent mission requirements. The more ground targets destroyed relative to the mission requirements, the better the performance.

a. *Number of prime targets destroyed*: A measure of the number of targets destroyed as listed on the ATO (i.e., all ground targets minus mobile SAM sites).

b. *Number of mobile surface to air missile (SAM) sites destroyed*. A measure of the number of SAM sites eliminated. Destroying mobile SAM sites is a measure of defensive performance in that they actively attack friendly forces and are not primary targets.

2. *Number of enemy aircraft destroyed*: A measure of the number of enemy aircraft the AWACS team/individual successfully destroy. Enemy aircraft randomly arrive during the scenario and follow arbitrary trajectories. The more enemy aircraft destroyed, the safer the high value assets (i.e., UAVs and tankers).

3. *Number of friendly assets lost to (ground and airborne) enemy attack*. A measure of the number of friendly assets (i.e., bombers, UAVs, fighters, and tankers) lost to enemy attack. One of the main objectives of AWACS crews is to ensure the safety of friendly aircraft. Thus the more friendly assets lost, the worse the team performance.

    a. *Number of high value assets (HVA) lost to enemy attack*. A measure of the number of tankers and UAVs lost to enemy attack. A major objective of AWACS crews is to ensure the safety of HVAs.

4. *Number of friendly assets lost due to fuel depletion*. A measure of the number of assets lost to inadequate fuel. Maintaining adequate fuel levels

and coordinating re-fueling is a major responsibility of the *Tanker WD* and the other WDs. The more assets lost to fuel loss, the worse the performance.

Qualitative outcome-related metrics. After the completion of each DDD mission scenario, subjects were required to complete an electronic survey that purportedly reveals subjects' beliefs about their performance and their team's performance. Additionally the electronic survey reveals subjects' beliefs about important aspects of each mission, i.e., strategies utilized, salient events, and potential future strategies. Ultimately, a qualitative analysis of individual beliefs about their team's performance and what was important during the mission permitted comparisons within teams and the opportunity to understand how individuals' strategies develop across trials.

After the completion of individual assessments, the team met face-to face to discuss what happened during the mission and to construct a joint belief assessment of how they performed, what strategies were important, and what should be done through future missions. During the mission de-briefing, the team jointly completed an electronic survey that purportedly reveals the teams' beliefs about each mission and their teams' performance. These data were examined in the same manner as the individual assessments (see above) in order to determine salient aspects of mission scenarios, strategy development, and learning.

Process-Related Performance

Quantitative metrics. Performance measures related to team coordination processes are operationally defined using four quantitative measures.

1. *Number of times Rules of Engagement (ROE) not followed*. A measure of the number of times *WD*s (controlling fighters and bombers) and the *SO* (controlling UAVs) do not coordinate when destroying enemy ground targets and the number of times civilians are killed (additive). Following the ROE is an important responsibility for all military personnel – coordinating attacks between fighters and UAVs and not killing civilians are important rules of engagement in the DDD scenarios. Thus the more un-coordinated attacks and civilians killed, the worse the performance.
2. *Number of friendly asset transfers*. A measure of the number of times *WD*s transferred their assets/roles to another *WD*. The number of asset transfer is directly related to the amount of coordination occurring during a scenario. Thus I posit that there will be a positive linear relation between number of asset transfers and performance.
3. *Number of communications between WDs*. A measure of the number of times *WD*s communicated using the available communication technologies.
4. *Number of friendly assets launched*. A measure of the number of times WDs launch fighters, bombers, or UAVs from the air-base. Launching too many assets may hinder performance because of an inability to control excessive aircraft. However, launching too few assets may limit the *WD*s' ability to control the enemy airspace.

Workload Metric. NASA TLX was utilized to assess subjective workload (Hart & Staveland, 1987). The NASA TLX is a subjective workload assessment tool that allows users to perform subjective workload assessments on operator(s) working with various human-machine systems. NASA TLX is a multi-dimensional rating procedure that derives an overall workload score based on an average of low to high ratings on six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration.

CHAPTER 5: EMPIRICAL EVALUATION IN AN AWACS SYNTHETIC TASK

A major driver of this research was to demonstrate the potential for exploring joint learning and performance through a simulated, complex work domain (i.e., AWACS BMC2). Specifically, by exploiting the opportunities provided by a synthetic environment, this research was directed at understanding the behavior of a simulated AWACS BMC2 team through a science of complexity, as opposed to a science supported by reduction and simplification. From the vantage point of complexity, a STE was developed to represent the meaningful dimensions (determined through several CWAs) of the AWACS BMC2 work domain and missions were constructed to afford operators an experience of domain constraints. With mission objective outlined in mission-specific ATOs, two trained teams (each) jointly worked through fifty dynamic and complex (15 minute) mission scenarios under varying conditions of organizational centralization (i.e., centralization versus de-centralization). For communication, operators were provided with a variety of technologies, including radio, chat, and a virtual whiteboard. Observing team behavior across missions provided an opportunity to understand how agents learned domain constraints and, in turn, jointly developed effective control solutions to dynamic situational problems. In other words, both teams were considered individually and together, as case studies that could be observed and evaluated to better understand how they made sense of, and controlled, the simulated AWACS BMC2 domain.

Case Studies

Case studies involve an in-depth, longitudinal evaluation of one or more cases (e.g., events, instances) and provide a systematic way of looking at events, exploring information, and reporting results. Yin (2002) states that case studies can be based on any combination of quantitative and qualitative evidence. Case studies can be used to understand the ‘why’ and ‘how’ of team dynamics and decision making by organizing data into patterns. Thus, case study data can be linked to theoretical propositions by using a ‘pattern-matching’ technique, i.e., whereby several pieces of information from the same case may be related to some theoretical proposition (Campbell, 1975).

Below, are two case studies representing both qualitative and quantitative accounts of Teams 1 and 2 coping with uncertainty through the AWACS BMC2 domain, as represented by a STE. Both case studies are presented together to draw attention to similar and contrasting behavioral patterns. The first data presented below reveal the effects of centralized versus de-centralized conditions on team performance and workload. Next, quantitative and qualitative data patterns are explored, providing evidence for organizational learning. In particular, the macro- and micro-structure of experimental data are explored to expose global variable patterns (i.e., learning trends). Finally, judgments related to actual performance outcomes and congruence among agent beliefs will be related to team performance.

Organizational Centralization

For the present study, teams were either centralized (i.e., WDs were required to request permission to commit any actions through the SD) or de-centralized (i.e., WDs were not required to request permission to commit actions). The effects of centralization were determined for outcome-related performance (i.e., targets: ground, air, SAM; loss: fuel-related, enemy-related), process-related performance (i.e., transfers and launches), workload, and common situation-awareness.

Outcome-Related Performance

Outcome measures address the actual results achieved and the impact of a team. For the present study, outcome-related performance measures were either loss-related (i.e., losses to fuel or to enemy) or target-related (i.e., prime targets, air targets, and SAMs). Across trials, we expected degree of centralization to significant effect all outcome-related performance metrics. Specifically, we expected both teams to eliminate more targets (i.e., prime, air, and SAMS) under de-centralized conditions because operators could quickly and autonomously eliminate ground targets without the additional time delays associated with requesting and receiving permission. Additionally, we expected more losses due to enemy attack during centralized conditions because rapid-responses to enemy attack would be slowed by permission requests. We did not expect organizational differences to effect losses due to fuel.

Results concerning the effects of centralization on outcome-related performance were mixed. Results from both teams do not indicate a significant effect of centralization condition on loss-related performance (see Figures 5.1 and 5.2). However, results were mixed in terms of the effect of centralization condition on outcome-related targeting performance. Wilcoxon Rank-Sum tests indicated that both Teams 1 and 2 eliminated significantly more air targets during de-centralized conditions [(Team 1: Centralized: M = 23.72, SD = 6.40; De-centralized: M = 28.56, SD = 5.14); (z = 1.84, N – ties = 16, p < .05, two tailed); (Team 2: Centralized: M = 26.44, SD = 6.17; De-centralized: M = 31.67, SD = 4.96); (z = 2.47, N – ties = 17, p < .05, two tailed); see Figures 5.3 and 5.4]. Additionally, Team 1 eliminated more SAM targets during de-centralized conditions (Centralized: M = 1.70; SD = 1.24; De-centralized: M = 2.5; SD = .92); (z = 2.02, N – ties

= 14, $p < .05$, two tailed). On the other hand, Team 2 eliminated significantly more prime targets during centralized conditions (Centralized: $M = 7.06$, $SD = 1.95$; De-centralized: $M = 5.89$, $SD = 2.08$); (z = 2.04, N – ties = 16, $p < .05$, two tailed).

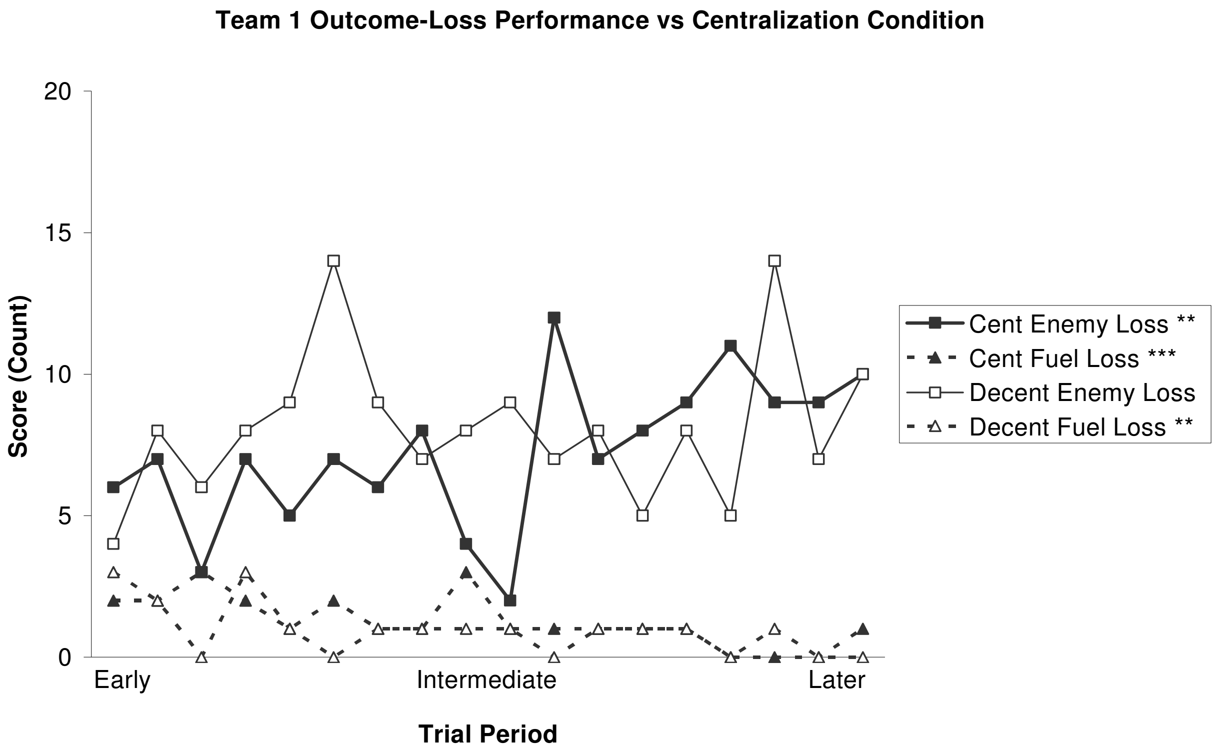


Figure 5.1. Team 1: outcome-related performance concerning losses due to fuel loss and enemy attack. Out of a total of 35 friendly assets.

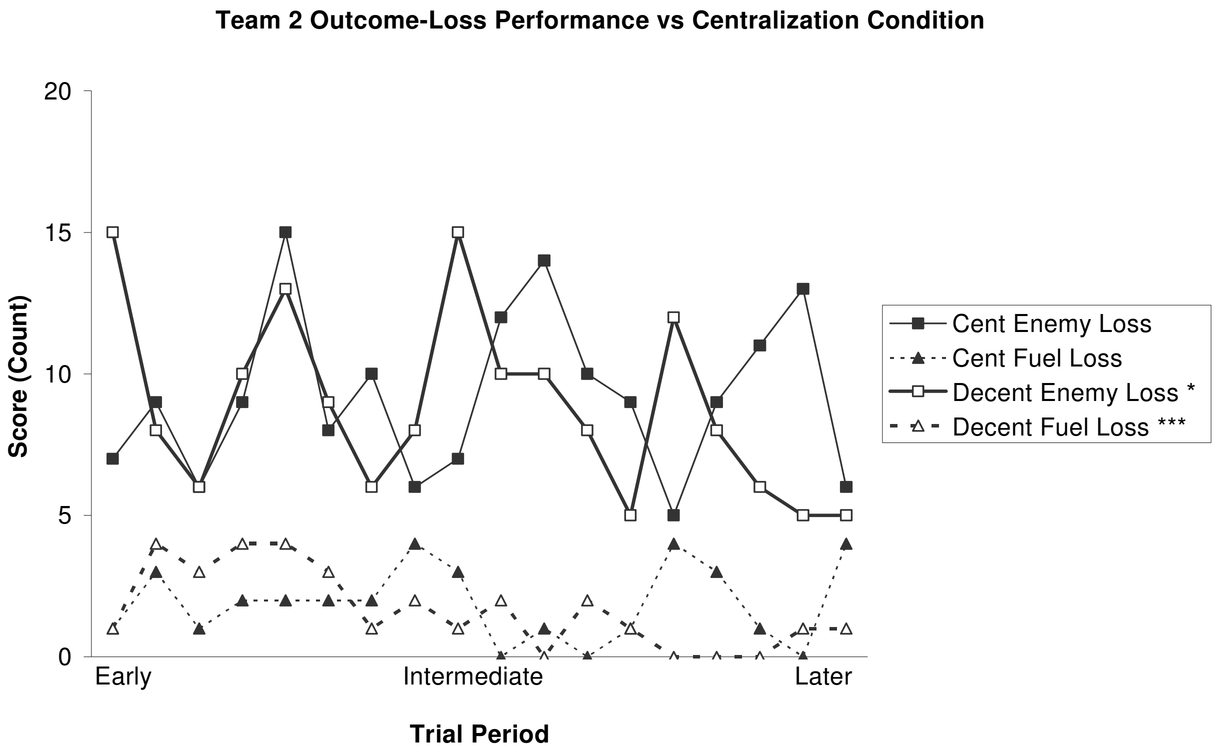


Figure 5.2. Team 2: outcome-related performance concerning losses due to fuel loss and enemy attack. Out of a total of 35 friendly assets.

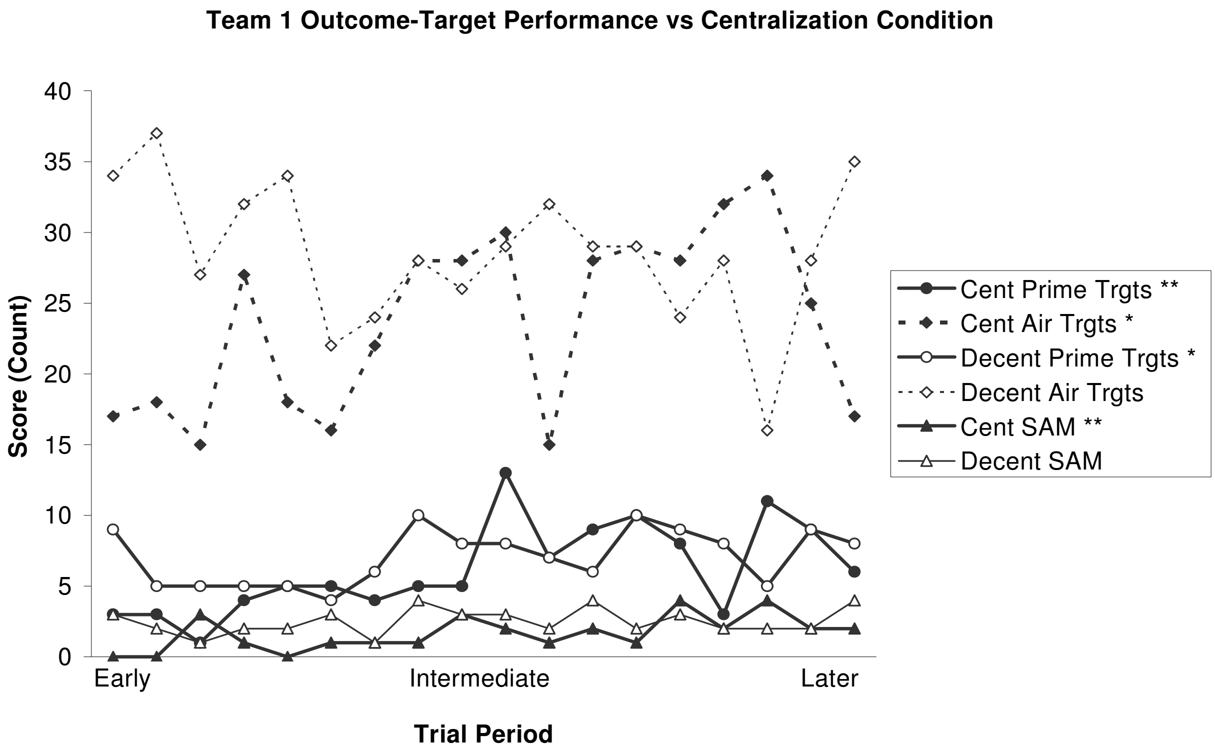


Figure 5.3. Team 1: outcome-related performance concerning targets eliminated. Out of 15 prime targets and 5 SAM sites per mission.

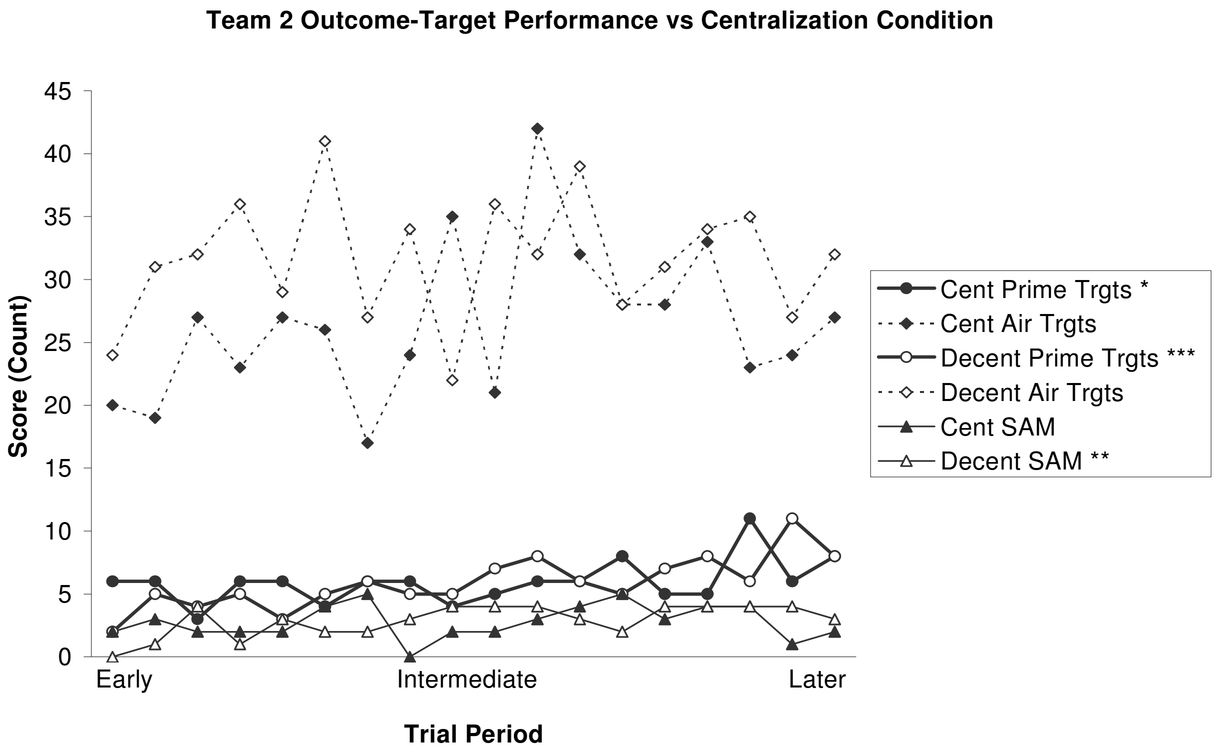


Figure 5.4. Team 2: outcome-related performance concerning targets eliminated. Out of 15 prime targets and 5 SAM sites per mission.

The mixed outcome performance results may have something to do with the nature of the targets. Both air and SAM targets represent more defense-oriented targets – neither is indicated on the ATO, but both represent a clear and present danger to friendly assets and prevent the accomplishment of mission objectives. Specifically, enemy air targets converge on friendly assets, thereby preventing access to priority targets and potentially killing friendly assets. Similarly, mobile SAM sites target friendly assets within their range. Conversely, prime targets represent offensive-oriented targets that are explicitly outlined in the ATO as priority mission objectives. Perhaps, both Teams eliminated more defense-oriented targets during de-centralized conditions because they did not have to request permission from the SD – thus, they were keen to attack non-priority targets instead of avoiding them. In terms of Team 2's elimination of more priority targets during centralized control conditions, we do not have a specific explanation.

Process-Related Performance

Both asset launches and transfers are characterized as process-related performance. As mentioned earlier, processes represent the actions or 'means' that cause a sequence of changes in the properties of a system. Processes are the means for transforming or moving from one system state to another. Thus, launching and transferring assets changes the configuration and dynamics of mission scenarios. Across trials, we expected operators to launch and transfer more assets during de-centralized conditions because without SD constraint operators would be free to launch and transfer assets according to mission demands without SD's potential veto – and, the added burden of requesting SD for permission. However, Wilcoxon Rank-Sum tests indicated that across trials for both Team 1 and Team 2, centralization condition did not significantly affect process-related performance (Team 1: Launches: ($z = 1.40$, N – ties = 16, $p > .05$, two tailed); Transfers: ($z = .03$, N – ties = 15, $p > .05$, two tailed; Team 2: Launches: ($z = .16$, N – ties = 14, $p > .05$, two tailed); Transfers: ($z = .67$, N – ties = 17, $p > .05$, two tailed); see Figures 5.5 and 5.6). In other words, centralization conditions did not affect the number of asset launches or transfers across trials for either Team 1 or 2.

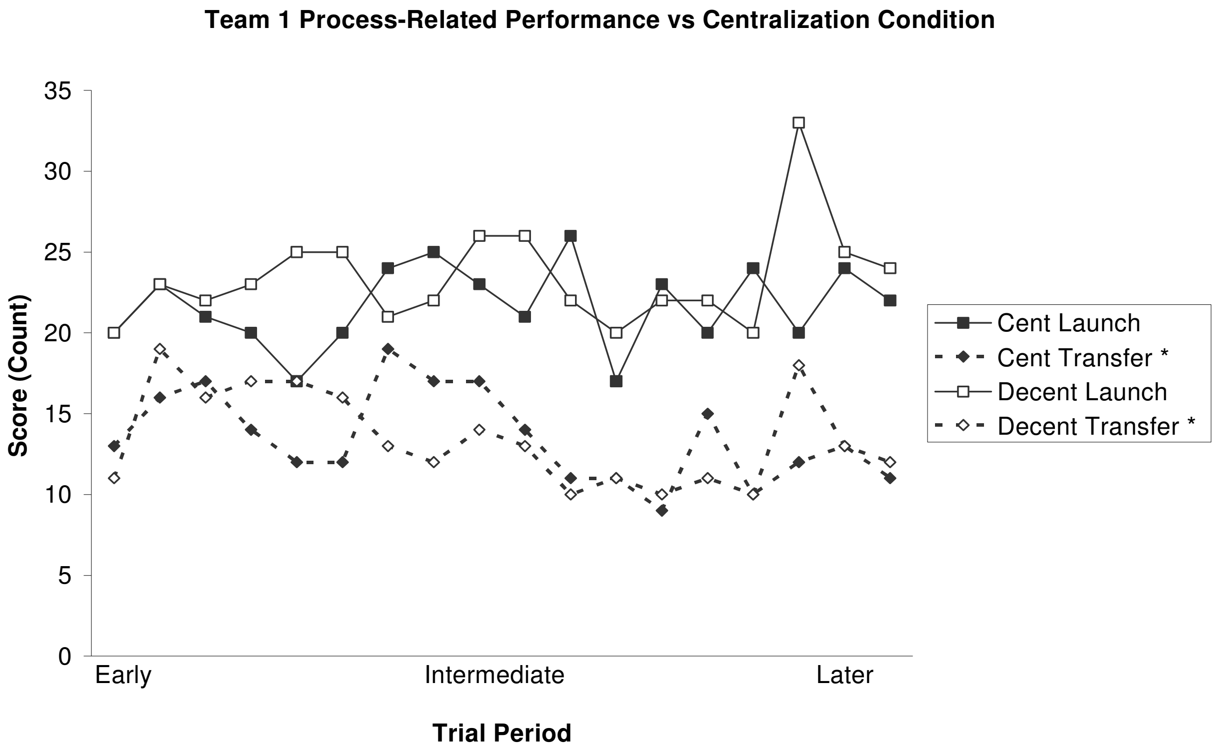


Figure 5.5. Team 1: Process-related performance by centralization condition across trial periods.

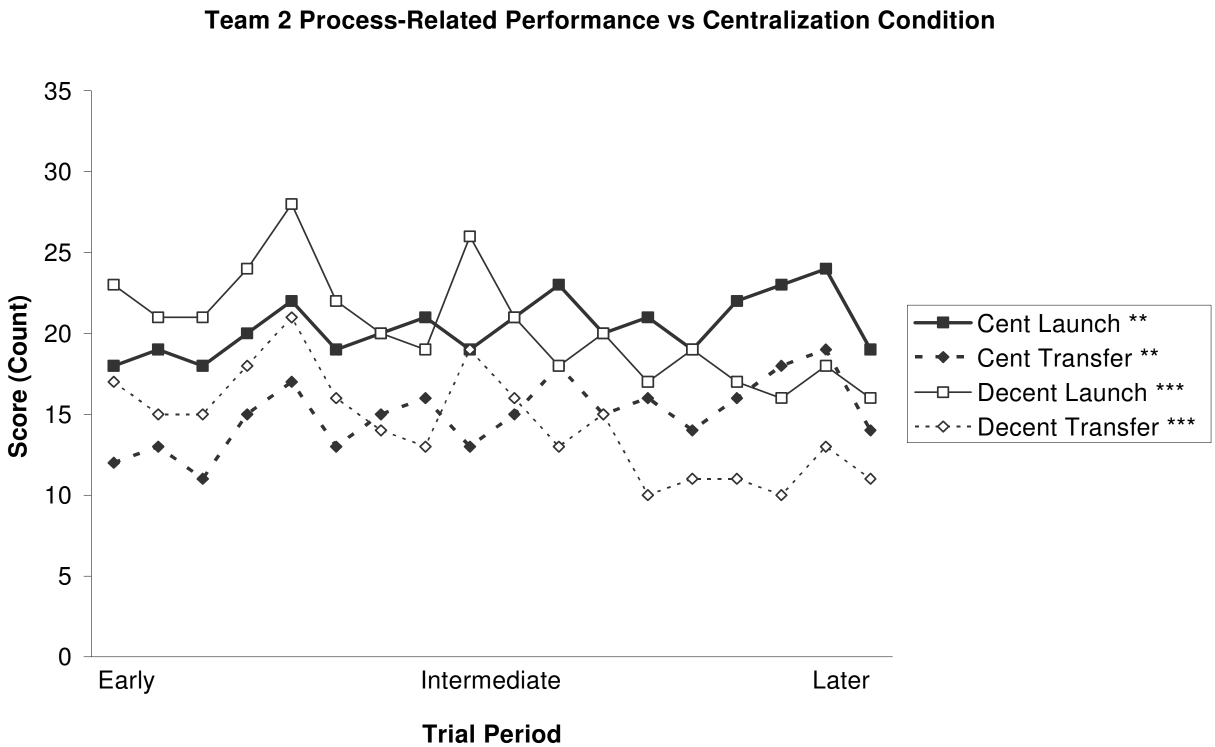


Figure 5.6. Team 2: Process-related performance by centralization condition across trial periods.

Workload

Subjective workload was evaluated using a modified version of the NASA TLX (Hart & Staveland, 1987; see above). We expected significantly higher perceived workload ratings for centralized conditions compared to de-centralized conditions. In particular, we expected that the added responsibility of requesting permission through the SD during centralized conditions – an additional constraint on action for the operators, would lead to higher perceived workload than during conditions where operators did not experience the additional action constraint. Results for Team 1 indicate no significant effect of centralization condition on perceived workload (see Figure 5.7). However, results from a Wilcoxon Rank-Sum test indicate that Team 2 perceived significantly higher workload during centralized conditions (Centralized: M = 63.33, SD = 2.64;

Decentralized: *M* = 60.89, *SD* = 2.40); (z = 2.44, N – ties = 17, $p < .05$, two tailed) thereby partially confirming our expectation that higher workload would be perceived during centralized conditions.

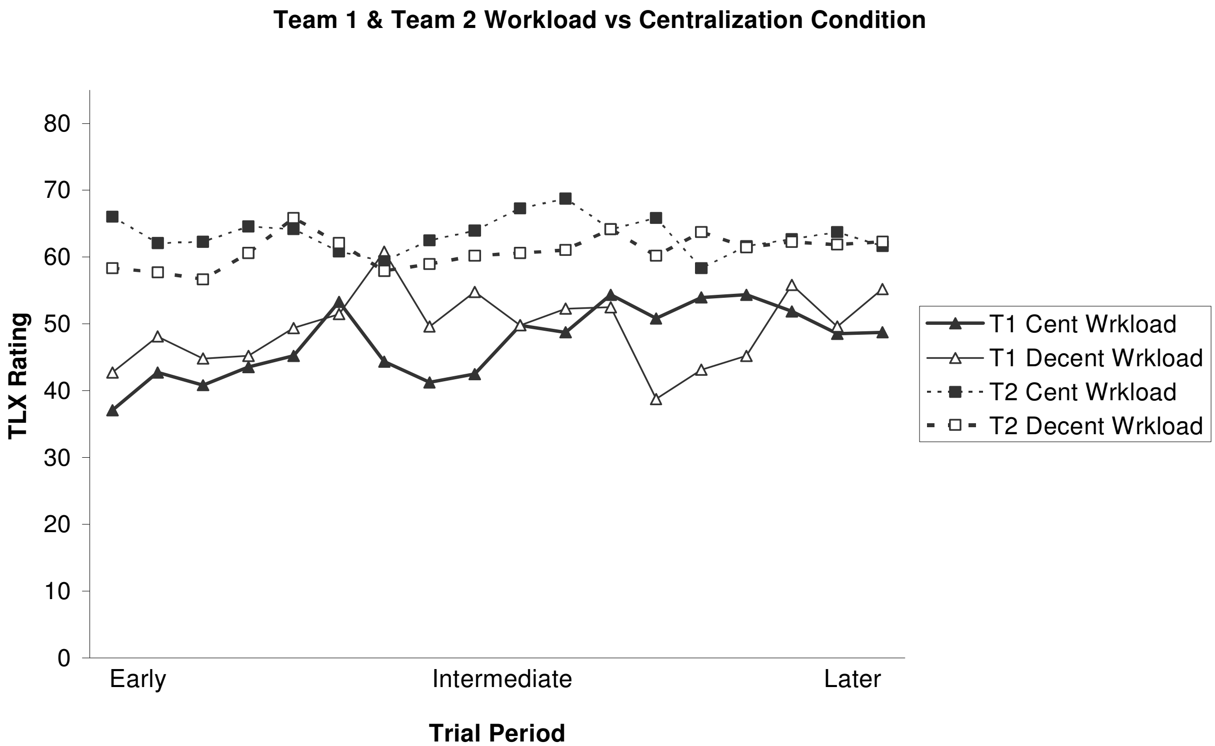


Figure 5.7. Teams 1 and 2: perceived workload by centralization condition.

A potential explanation for the lack of a significant effect of centralization condition on perceived workload for Team 1 is that they incorporated a 'work-around' strategy to cope with the added burden of requesting permission (see section below on organizational learning and constraints on information). Although, the evidence primarily comes from open-ended responses (the chat data do not differentiate between team), Team 1 appears to have incorporated a strategy of utilizing the chat tool to perform redundant requests for permission from the SD (beginning trial 3; see below). Specifically, after trial 2, Team 1's open-ended survey indicates a "suggestion for SD to use IM so to increase speed of communication". Additionally, after trial 3, "all" operators on Team 2 "agreed SD should continue to use IM". Finally, after trial 11, Team 1 responds, "all agree much easier and less radio chatter without having to ask SD permission". On the other hand, from the open-ended response data, it appears that Team 2 did not adopt a similar strategy – thus, utilizing the radio channel across trials.

Open-ended surveys indicated that both teams were frustrated by the centralized conditions. For example, Team 2's Checkin WD (after trial 21) reports in an open-ended response that "having to ask permission from SD raises the frustration, slows the moves, makes us as targets more vulnerable due to the time it takes to defend ourselves or launch planes to defend ourselves." Additionally, after trial 23, Team 1's SO reports that "without SD we function as a single unit" and they maintain the "belief that reintroduction of SD slows team down and causes reduction in scores". Also, after trial 31, Team 1' Checkin WD notes that they "had to ask SD permission and this upped the temporal demand as I tried not to die while asking for permission". Finally, in Team 2's 'team' open-ended briefing after trial 11, they indicate, "having to request permission from SD has a severe impact on quick responses." Thus, it appears that both teams perceived added 'workload' and frustration from the requirement to request permission from the SD. Specifically, operators believed that centralized conditions imposed a severe temporal constraint on their ability to rapidly respond to mission dynamics and, therefore made assets vulnerable to enemy attack.

Results from NASA TLX ratings across all conditions reveal relatively consistent workload responses across Team 2, whereas Team 1's workload ratings exhibited a significant positive trend across trials; $t(43) = 6.61$, $p < .001$ (see Figure 5.7).

Additionally, analyses indicate a significant difference between Team 1 and Team 2's perceived workload (Team 1: M = 48.02, SD = 5.34; Team 2: M = 61.86, SD = 2.69). $t(44) = -16.75$, $p < .05$. When workload data are plotted separately for centralization condition and per operator (see Figures 5.8), it appears that both Teams' perceptions of workload increase across trials during centralized conditions, but remain relatively consistent across de-centralized conditions. One possible explanation as to why centralized conditions led each Team's perceived workload to exhibit significant positive trends, whereas de-centralized conditions did not have the same effect is that frustration under centralized conditions could increase with skill and confidence in the task. That is, as operators become more confident in their own decisions it is more frustrating to have to get permission. Analyses of both Teams' operator perceived frustration (NASA TLX sub-scale item) does not support this conclusion (see Figure 5.9). Indeed, it only appears that Team 2's Tanker WD's data during de-centralized conditions and both Team's SO's data during centralized and Team 2's SO during de-centralized conditions exhibit a significant positive trend across trials.

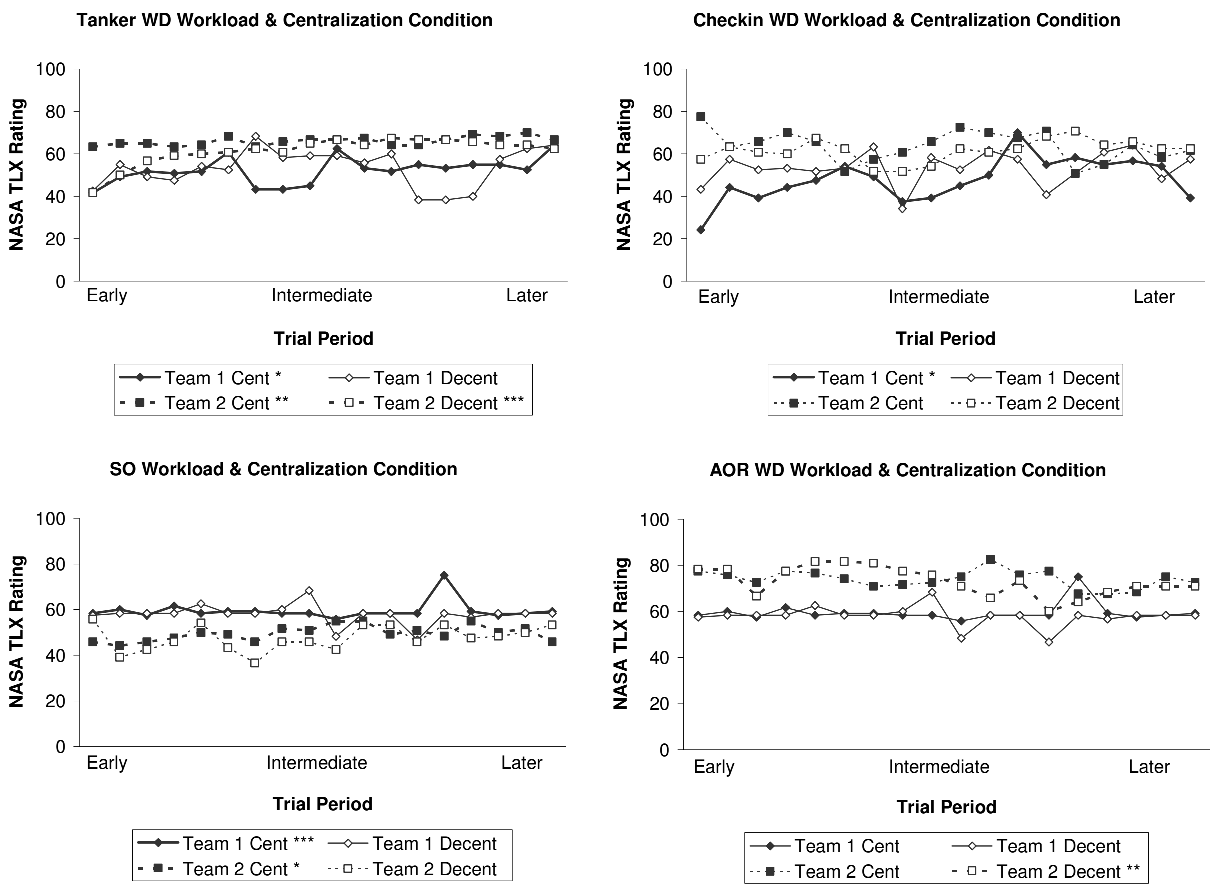


Figure 5.8. Teams 1 and 2: perceived workload (NASA TLX totals) for each operator across centralized and de-centralized conditions.

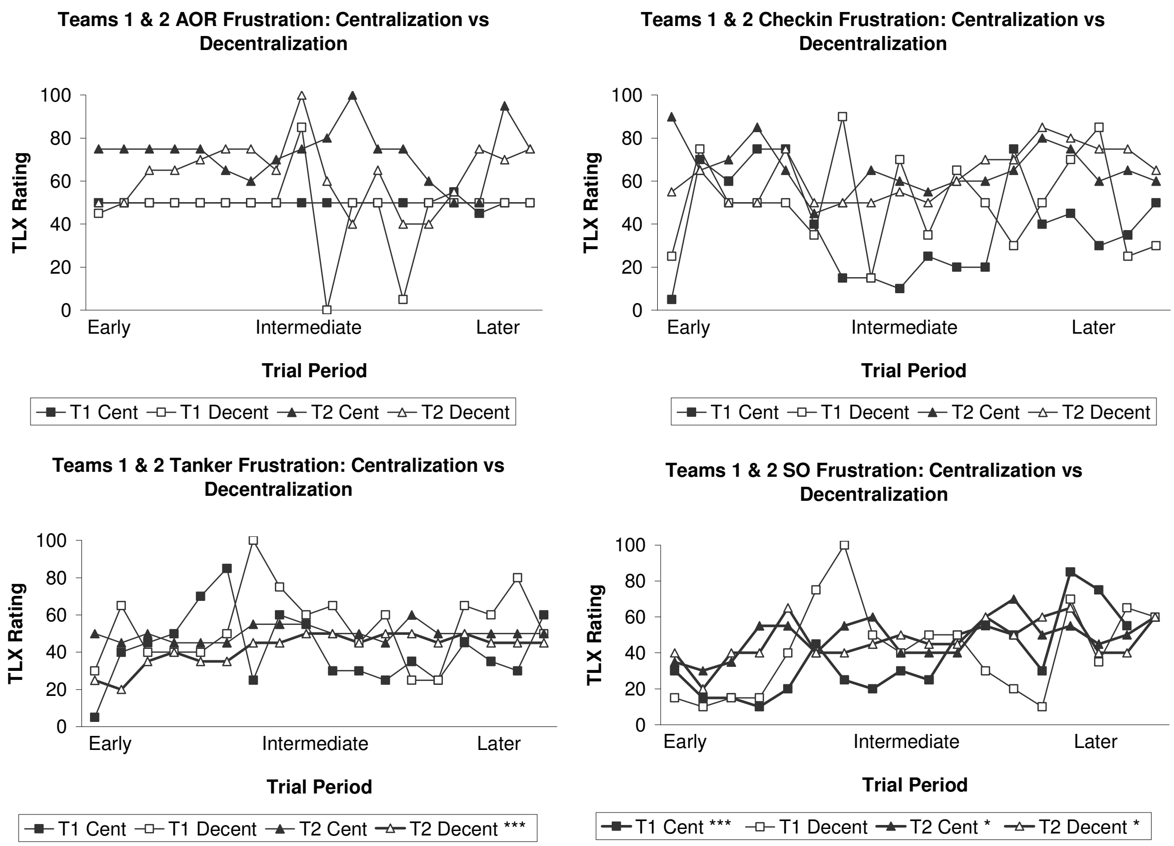


Figure 5.9. Teams 1 and 2: perceived frustration (NASA TLX sub-scale) for each operator across centralized and de-centralized conditions.

Overall, results concerning the effects of centralized versus de-centralized conditions on performance are mixed. In general, the data acquired from the present study do not support any firm conclusions about the effects of either centralization condition on process-related or outcome-related performance. However, results from open-ended responses and the NASA TLX (for Team 2) indicate that centralized conditions lead to *perceptions* of higher ‘workload’, frustration, and a reduction in performance. Indeed, it seems intuitive that the magnitude of the time-delay due to requesting and receiving permission to commit acts within the battlespace would have an effect on workload and performance, such that higher time-delays would reduce performance (agents would have less time to respond to time-critical events) and increase frustration. Further research is required to better understand the effects of organizational centralization and the magnitude of time-delays on performance and workload.

Organizational Learning

In the previous chapters, the scale of complexity was defined according to the degree of coupling and dimensionality characterizing a system. When systems exhibit high complexity (i.e., loose coupling and high dimensionality), the maintenance of stability becomes problematic: standards and plans (i.e., effective control strategies for tightly coupled, low dimensional systems) are not effective because the variety exhibited by the domain is greater than the variety inherent to solutions. Thus, continuous organizational *learning* through mutual adjustment was presented as an adaptive process of stabilizing complex work domains.

Evidence for learning will first be explored by identifying significant process- and outcome-related performance trends at the macro-level. Specifically, performance data plotted across trials and centralization conditions reveals significant positive and negative trends that are related to learning. Next, process- and outcome-related performance will be examined at the micro-level to determine a) the relevance of specific temporal periods on learning and b) patterns of cross-correlations among performance measures. In addition, global variable patterns at the macro- and micro-level will be described in terms of specific adaptive control strategies employed by teams through mission scenarios.

Macro-Structure of Data

Outcome-related targeting performance. Across trials, for both Teams, we expected significant positive trends for the number of prime targets eliminated, air targets, and SAM sites. Specifically, we believed that through experience with mission scenarios, Teams would learn to eliminate greater numbers of prime targets, in part by learning how to cope with (i.e., eliminate) potentially threatening enemy assets (i.e., air targets and SAM sites). For both teams, data trends across trials indicate significant positive trends in number of prime targets eliminated (Team 1: $t(43) = 3.89$, p .001; Team 2: $t(43) = 7.21$, $p < .05$; see Figure 5.10). Although, Team 2's prime target performance significantly differed across centralization conditions (see above), during both centralized and de-centralized conditions a significant positive trend in prime targets eliminated is observed (centralized: $t(16) = 2.07$, $p < .05$; de-centralized: $t(16) = 5.15$, $p < .05$; see Figure 5.10). Additionally, data for both Teams indicate significant positive trends for number of SAM sites eliminated (Team 1: $t(43) = 3.21$, $p < .05$; Team 2: $t(43) = 2.61$, $p < .05$; see Figure 5.10). However, when considering the significant difference in number of SAM sites eliminated by Team 1 during different centralization conditions, data only indicate a significant positive trend in number of SAM sites eliminated during centralized conditions; $t(16) = 2.78$, $p < .05$ (see Figure 5.10). Finally, for Team 1 data indicate a significant positive trend in the number of air targets eliminated during centralized conditions; $t(16) = 2.31$, $p < .05$ (see Figure 5.10).

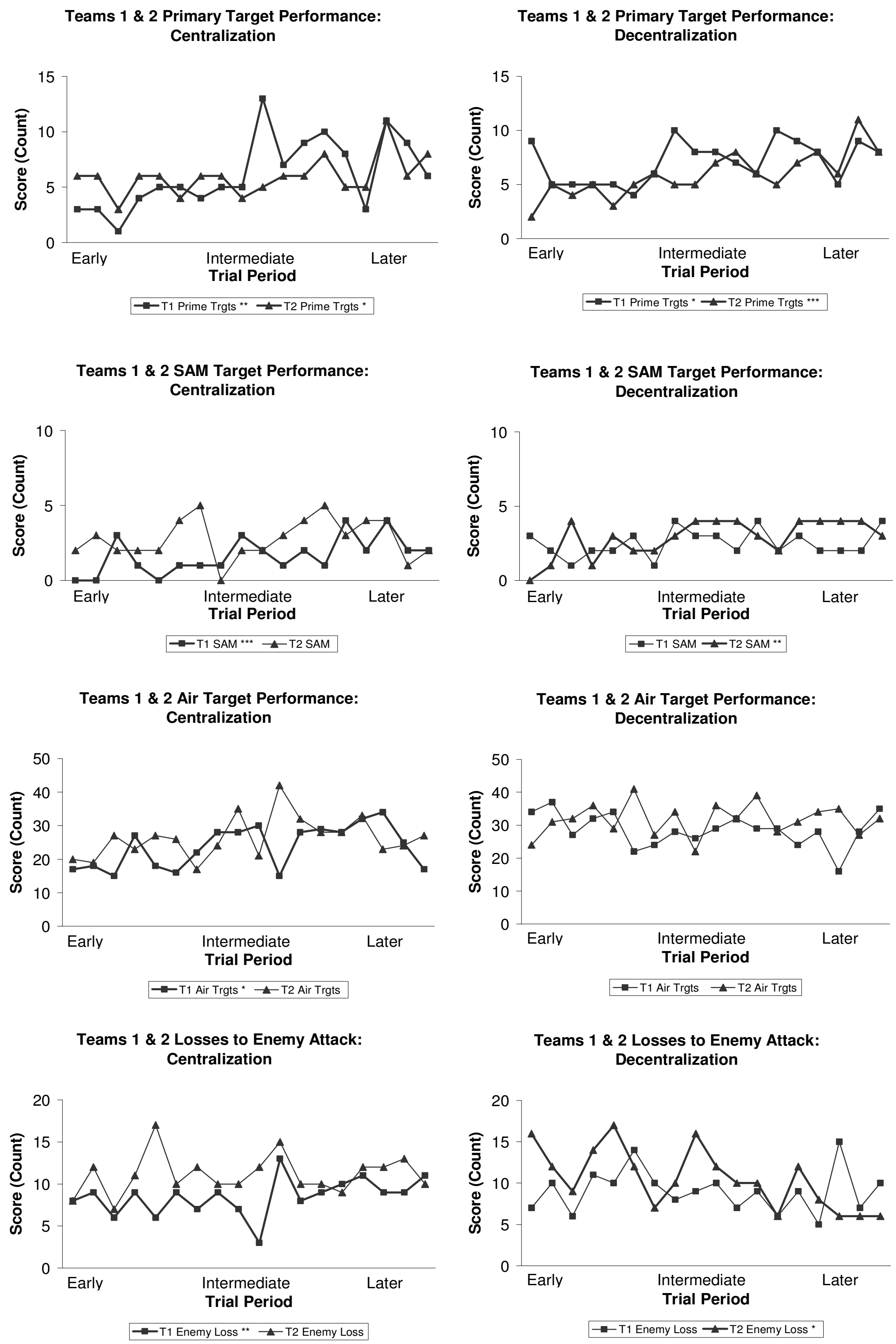


Figure 5.10. Teams 1 and 2: data trends for primary target performance, SAM target performance, air target performance, and losses to enemy attack performance by centralization condition.

From the above data it appears that both Teams learned to eliminate more prime targets across trials. For Team 1, the number of prime targets eliminated remained constant until half way through the experiment, and then there is a step increase to a higher level (from trial 22 to 50; intermediate through later trial periods). Perhaps, this is due to a qualitative shift in strategy led to an increase in the number of prime targets eliminated (the Checkin WD assisted in eliminating ground targets; see below). In terms of Team 2, the number of prime targets eliminated appears to increase at a relatively stable rate (Team 2 did not exhibit the same qualitative shift in strategy as Team 1).

Eliminating prime targets is an integral function of the AWACS BMC2 team as outlined in the ATO. Indeed, both Teams recognized the importance of concentrating effort on eliminating prime targets and improving performance. For example, after trial 24, Team 1's Tanker WD commented in the open-ended survey that the Team "did a good job, we took out all the primary targets". In addition, Teams recognized improvements in their targeting performance – for example, after trial 14, Team 2's Tanker WD commented in the open-ended survey, "we improved from last time, we communicated very well and attacked more ground targets". Thus, Teams learned to make prime targets a priority and believed that they were learning to effectively execute this objective.

Both Teams believed that at least part of their outcome-related performance improvement was due to enhanced coordination among operators. For example, after trial 42, Team 1's SD commented in the open-ended survey that, "Tanker, Checkin, and SO work together as a team well with Tanker bombing ground targets while Checkin provides support. As a team they follow the priorities on the ATO list well". Also, after trial 2, Team 2's Tanker WD comments on the open-ended survey, "I think we did really well in communicating with each other that time, we had great teamwork in destroying our ground targets. AOR and I worked great together in re-fueling and restocking our aircrafts and targeting the enemy's planes. So, over all I think we did much better and I think we improve each and every time we do a mission". Finally, after trial 38, Team 2's Tanker WD comments in the open-ended survey, "we coordinated attacks quickly and managed to take out a lot of ground targets". From the above sample of comments and the significant trends in targeting performance, it appears that both Teams learned to effectively coordinate and communicate in order to accomplish the mission objective of eliminating prime targets.

Both Teams appear to eliminate SAM sites at a relatively consistent rate across trials. Although, SAM sites were not a priority, they were potential threats to friendly assets and eliminating them provided assurance against potential friendly losses. Additionally, air targets were a potential threat to friendly assets. For Team 1, as mentioned above, there is a significant positive trend in the number of air targets eliminated during centralized conditions. We believe that this is associated with the elimination of enemy air bases (see Figure 5.11). Specifically, the more enemy air bases eliminated within the first seven minutes of a scenario (there were three enemy air bases per mission), the fewer enemy air assets launched into the AOR (note: as a performance metric, elimination of an enemy air base did not include potential enemy air assets that, in 'real' circumstances would be present at the air base; only the enemy air base was counted as an eliminated target). Although the micro-structure of the data will be discussed below, it is important to note that for Team 1, the number of air targets eliminated was positively correlated with number of enemy air bases eliminated during centralized conditions; r = .27; $t(34) = 3.28$, $p < .05$ (correlations were not significant for Team 2 or Team 1 under de-centralized conditions). Although, it appears that the number of air targets eliminated for Team 1 during centralized conditions is related to an increase in number of airbases eliminated, we cannot establish a direction of causation.

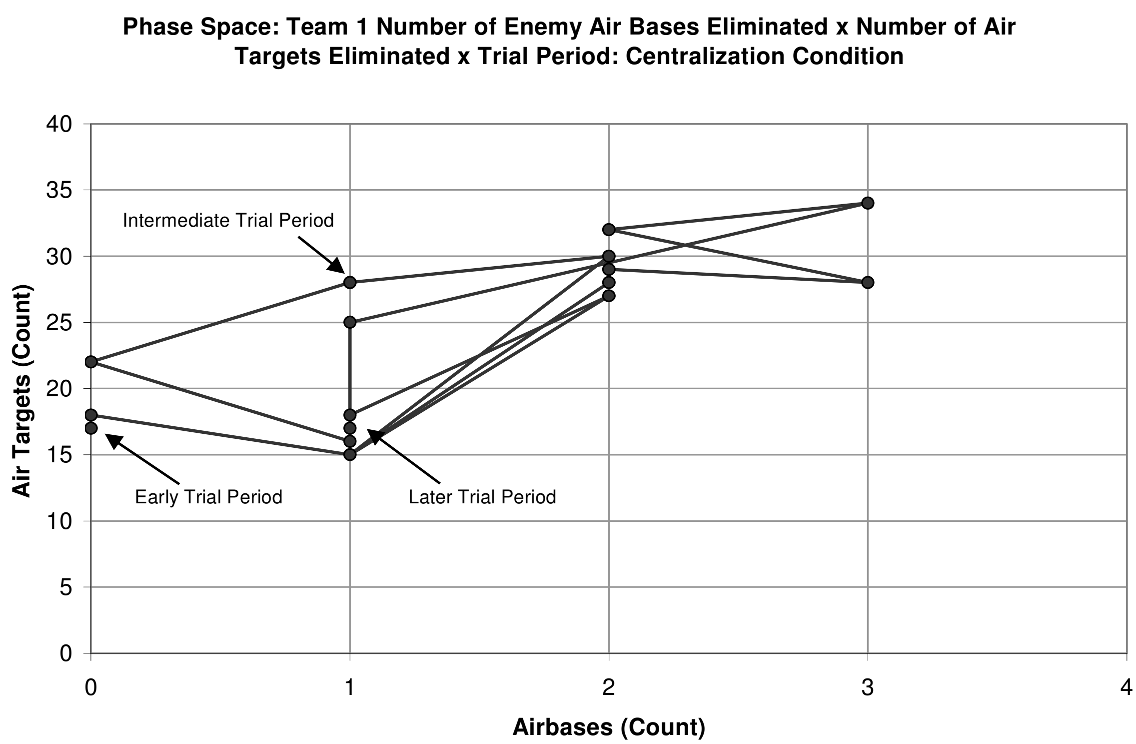


Figure 5.11. Team 1: phase-space of the number of enemy air bases x air targets eliminated x time during centralization conditions.

Outcome-related asset loss performance. We expected that for both Teams, across trials, negative trends would be exhibited for asset losses due to fuel depletion and enemy attack. This expectation is based on our belief that Teams would learn how to cope with fuel concerns and enemy attacks. In terms of losses due to fuel depletion, data for both Teams indicate significant negative trends across all trials (Team 1: $t(43) = 4.32$, $p < .05$; Team 2: $t(43) = 2.78$, $p < .05$; see Figure 5.10). In terms of assets lost to enemy attack, Team 1's data indicate a significant positive trend in the number of assets lost to enemy attack across all trials $t(43) = 4.32$, $p < .05$ (see Figure 5.10). Thus, both Teams learned to cope with fuel concerns whereas neither Team learned to manage enemy attacks – indeed, Team 1's management of enemy attacks has decreased.

For both Teams, significant negative trends in the amount of friendly assets lost to fuel depletion appear to be consistent across trials. Indeed, during the second half of the experiments, both Teams appear to have reduced the number of assets lost to fuel depletion to near zero levels. On the other hand, the number of assets lost to enemy attacks for both Teams appears to be variable across trials. Again, the number of friendly assets lost to enemy attack might be associated with the number of enemy air bases eliminated during the first seven minutes of each scenario (see last section on enemy air targets). There is some support for this for Team 2 during centralized conditions – number of enemy losses is positively correlated with number of enemy air bases eliminated, r = .36; $t(34) = 2.25$, $p < .05$. However, we cannot explain the remainder of the variability in losses to enemy attack.

For Team 1, around half way through the experiment, there appears to be a sharp increase in the number of assets lost to enemy attack during centralized conditions (and, Team 1's losses to enemy attack exhibit a significant positive trend across trials). We believe that this also is associated with the qualitative shift in strategy exhibited by Team 1 (discussed below). In particular, we believe it is associated with Checkin WD's efforts to manage additional friendly assets in the AOR. Specifically, starting around half way through the experiment, Team 1's Checkin WD learned to manage friendly assets – initially, more assets were lost to enemy attack and as the Checkin WD learned to manage more assets (although, the number of assets lost to enemy attack did not reduce to levels displayed prior to the shift in strategy, this was probably due to the increased risk of launching more aircraft).

Data from open-ended surveys indicate that both Teams learned to recognize fuel concerns and learned to manage losses due to fuel depletion. Indeed, after trial 8, Team 1 commented that they “need to keep a closer eye on the fuel”; after trial 10, Team 1 commented, “too many planes are going down due to lack of fuel. Tanker asks that teammates are vigilant on checking their fuel and inform him in ample time to restock and refuel”. In terms of Team 2’s comments, after trial 2, AOR WD comments, “we managed to keep planes in the air longer, we actually re-fueled!” Referring to Team 2’s coping with fuel concerns, after trial 4, Tanker WD comments, “I think that we improved on refueling”, and after trial 5, Tanker WD comments, “overall we did a real good job refueling and working as a team…” Thus, both Teams appear to have learned to pay attention to fuel concerns and to coordinate re-fueling with Tanker WDs.

Process-related performance. We did not expect a particular trend in the number of assets launched and transferred across trials. On the one hand, we believed that across trials Teams might exhibit a negative trend in launches and transfers because they learned to lose fewer assets to fuel depletion and enemy attack. However, on the other hand, we thought that across trials Teams might exhibit a positive trend in launches and transfers because they learned how to simultaneously manage multiple assets and continuously transfer roles and responsibilities. Results from both Teams process-related performance indicate a significant negative trend in the number of assets transferred across trials (Team 1: $t(43) = 3.49$, $p < .05$; Team 2: $t(43) = 3.04$, $p < .05$; see Figure 5.10).

Additionally, results from Team 2 indicate a significant negative trend in the number of asset launches across trials; $t(43) = 4.79$, $p < .05$ (see Figure 5.10).

For Team 1, launches and transfers appear to move in parallel during the first half of the experiment. However, after the second half of the experiment, launches and transfers appear to diverge – the number of transfers seems to decline relative to launches. We believe that this divergence is due to a qualitative shift in Team 1's performance strategy during the second half of the experiment wherein the Checkin WD maintained control over friendly assets, thereby transferring fewer of them to other operators (see below for more on this). For Team 2, launches and transfers appear to move in parallel across all trials. We believe that this is due to the Checkin WD systematically launching and transferring assets to operators – Team 2's Checkin WD did not maintain control over friendly assets (as Team 1's Checkin WD did during later trials).

In this section, the macro-structure of outcome- and process-related performance data were discussed in terms of significant linear trends across trials. To offer some qualitative support to general learning trends, open-ended responses from individual and team surveys were related to the quantitative data. Overall, it appears that across trials, both Teams learned to cope with fuel concerns and progressively eliminate more targets (prime targets were of particular importance, but they also learned to eliminate more SAM sites). In the next section, the micro-structure of performance data will be explored in detail to expose a general qualitative shift in strategy for Team 1.

Micro-Structure of Data and Qualitative Shifts in Strategy and Performance

To get a more detailed understanding of the learning processes, we parsed the data into temporal segments and examined correlations among the various measures. Specifically, to explore learning trends during different temporal periods of trials, data were parsed into segments within trials – during early, intermediate, and later periods of trials. Parsing data along temporal phases of battle has the potential to reveal mission events that might only show up during a specific temporal period of trials. Additionally, individual performance metrics were correlated to uncover specific goal trade-offs and/or priority shifts.

Micro-level trends. For both Teams, performance data were split up into three temporal periods: early (i.e., the first four minutes of trials), intermediate (i.e., the second four minutes of trials), and later (i.e., the final six minutes of trials; see Tables 5.1 and 5.2). First, for both Teams, during the intermediate period of trials, data indicate significant negative trends in assets lost to fuel (Team 1: $t(43) = 4.32$, $p < .05$; Team 2: $t(43) = 4.58$, $p < .05$). Results can be explained in terms of the characteristics of assets in all mission scenarios – upon starting each mission, assets have a variable amount of fuel that will last several minutes into each scenario. Ultimately, assets crash if they are not refueled by the intermediate point of scenarios. Thus, from the data, it appears that across trials, both teams learned to lose fewer assets to fuel depletion (that would typically occur during the intermediate point of trials).

Table 5.1

Pearson-r Values for Team 1: Cumulative and Temporal Performance

Performance Metric	Early = 4 min.	Inter = 8 min.	Late = 14 min.	Cum
Grnd Trgts	.32+ *	.26+ *	.33+ *	.52+ ***
Prime Trgts				.51+ ***
Air Trgts	.14+	.14+	.00+	.10+
Enemy Loss	.14+	.36+ **	.33+ *	.48+ **
Fuel Loss	.00+	.55- ***	.00-	.55- ***
Launches	.14+	.10-	.10-	.14+
Transfers	.10+	.28- *	.41- **	.42- **
HVA Loss	.17+	.17+	.35+ **	.37+ **
SAM Def				.44+ **

* $p < .05$; ** $p < .01$; *** $p < .001$

Table 5.2

Pearson-r Values for Team 2: Cumulative and Temporal Performance

Performance Metric	Early = 4 min.	Inter = 8 min.	Late = 14 min.	Cum
Grnd Trgts	.50+ ***	.32+ *	.44+ **	.69+ ***
Prime Trgts				.73+ ***
Air Trgts	.14+	.24+	.10+	.22+
Enemy Loss	.00-	.10-	.14-	.22-
Fuel Loss	N/A	.46- **	.00+	.39- **
Launches	.10+	.10-	.59- ***	.59- ***
Transfers	.24+	.10-	.60- ***	.47- **
HVA Loss	.17+	.00+	.10+	.14+
SAM Def				.37+ **

* $p < .05$; ** $p < .01$; *** $p < .001$

In terms of ground targets eliminated during trials, micro-trends support a general, positive linear trend in number of ground targets eliminated through trials (see above section on macro-structure). In regard to micro-level trends in Team 1's performance, losses to enemy attack exhibit positive trends during intermediate and later trial periods, HVA losses exhibit significant positive trends during later trial periods. We believe that the discrepancy between Team 1 and Team 2's process-related (i.e., asset launches and transfers) and air target performance data and was associated with a qualitative shift in strategy employed by Team 1, but not Team 2 (see below). Thus, Team 1's data did not indicate any significant trend in terms of asset transfers, but exhibited a negative trend in number of transfers during intermediate and later periods of trials. Team 2, on the other hand, displayed significant negative trends in number of launches and transfers during later trial periods. These data imply that Team 1's Checkin WD launched a consistent amount of assets throughout each trial, yet transferred fewer assets (i.e., instead, personally managed) as missions proceeded. Similarly, after launching necessary assets for operators during early periods of trials, Team 1's Checkin WD managed additional assets – that were lost to enemy attack, explaining the positive micro-level trends in losses to enemy attack during intermediate and later trials. Conversely, Team 2's Checkin WD launched and transferred consistently during early and intermediate periods of trials, whereas they launched *and* transferred significantly fewer assets during later trial periods (note the similarities in trends).

Performance measure relationships. Performance measures were cross-correlated to reveal potential relationships (i.e., goal trade-offs and/or priority shifts) among process- and outcome-related performance variables (see Tables 5.3 and 5.4). By exploring data patterns across temporal periods of performance, cross-correlations among performance variables and qualitative open-ended survey data obtained from the individual- and team-level, qualitative shifts in team strategy and performance are revealed.

Table 5.3

Pearson-r Values and Significance for Team 1: Performance Measure Correlation Matrix

Performance Metric	Air Trgts	Enemy Loss	Fuel Loss	Launches	Transfers	SAM
Grnd Trgts	.20 *	.04+	.32- **	.12-	.36- ***	N/A
Air Trgts		.22- *	.00	.09-	.11-	.19+ *
Enemy Loss			.41- ***	.47+ ***	.06+	.29+ **
Fuel Loss				.15-	.32+ **	.13-
Launches					.42+ ***	.02+
Prime Trgts						.43+ ***

*p < .05; ** p < .01; *** p < .001

Table 5.4

Pearson-r Values and Significance for Team 2: Performance Measure Correlation Matrix

Performance Metric	Air Trgts	Enemy Loss	Fuel Loss	Launches	Transfers	SAM
Grnd Trgts	.00	.08-	.37- ***	.40- ***	.28- **	N/A
Air Trgts		.01-	.14+	.15-	.13-	.02-
Enemy Loss			.24- *	.65+ ***	.65+ ***	.03+
Fuel Loss				.28+ **	.29+ **	.33- ***
Launches					.96+ ***	.20- *
Prime Trgts						.48+ ***

* p < .05; ** p < .01; *** p < .001

Although, we had expectations when it came to trends in the macro-structure of the data (see above), we did not have any specific expectations regarding micro-level performance measure relationships - although, we expected that performance measures would be correlated to a moderate degree due to the nature of sampling performance from a work domain (Bommer, Johnson, Rich, Podsakoff, and Mackenzie; 1995). Specifically, performance measures collected through the experiment are all related to behaviors and outcomes exhibited by Teams – it is normal for those behaviors and outcomes to be related.

For both Teams 1 and 2, it appears that losses due to fuel depletion is negatively associated with the number of ground targets eliminated (Team 1: $t(88) = 3.17$, $p < .05$; Team 2: $t(88) = 3.74$, $p < .05$; see Tables 5.3 and 5.4). Indeed, losing assets to fuel would limit the number of assets available to eliminate ground targets. Similarly, one would expect the elimination of SAM sites to be related to number of prime targets eliminated because SAM sites pose an immediate threat to friendly assets attempting to eliminate prime targets. Indeed, for both Teams, number of SAM sites eliminated is positively related to number of prime targets eliminated (Team 1: $t(88) = 4.47$, $p < .05$; Team 2: $t(88) = 5.13$, $p < .05$; see Tables 5.3 and 5.4).

For both Teams, transfers appear to be negatively related to ground targets eliminated (Team 1: $t(88) = 3.62$, $p < .05$; Team 2: $t(88) = 2.74$, $p < .05$; see Tables 5.3 and 5.4). However, only Team 2 displays a negative correlation for number of launches and ground targets eliminated; $t(88) = 3.74$, $p < .05$ (see Table 5.4). Perhaps, this discrepancy is related to a qualitative shift in Team 1's strategy. Specifically, perhaps Team 1's Checkin WD is launching and holding onto assets, instead of transferring them to other operators. Below, details concerning how these patterns relate to a qualitative shift in Team 1's performance will be discussed.

For both Teams, transfers are positively related to launches (Team 1: $t(88) = 4.34$, p .001; Team 2: $t(88) = 32.16$, $p < .05$; see Tables 5.3 and 5.4). However, correlations among process-related performance metrics are particularly strong for Team 2, accounting for around 92 percent of the variance (compared to 18 percent for Team 1). Of related interest, losses due to enemy attack are positively correlated with number of launches for Team 1; $t(88) = 5.00$, $p < .05$, but not with transfers, whereas for Team 2, losses due to enemy attack are correlated with both launches and transfers (launches: $t(88) = 8.02$, $p < .05$; transfers: $t(88) = 8.02$, $p < .05$; see Tables 5.3 and 5.4). Again, we believe these process-related performance discrepancies between Teams 1 and 2 are related to a qualitative shift in Team 1's strategy (see below). In terms of correlations among other process- and outcome-related performance metrics, we do not have any specific explanations.

Qualitative shift in strategy. Across trials, an interesting pattern was discovered across micro- and macro-levels of performance. This pattern was discussed in prior sections on the macro-structure of performance data – in terms of improved prime target elimination and increased asset losses to enemy, and in terms of micro-level trends in performance data. We believe that patterns in the micro- and macro-structure of data indicate a qualitative shift in Team 1's strategy during the second half of the experiment. Specifically, it appears that about half way through the experiment (around trial 22; intermediate trial period) Team 1 employed a strategy of having the Checkin WD manage friendly assets to assist in eliminating ground targets and provide close-air support. Evidence for a shift in Team 1's strategy can be seen half-way through trials in terms of ground targets eliminated, assets lost to enemy attack, the discrepancy between process-related performance coupling that is apparent across Team 2's data, but not Team 1's data, and through Checkin WDs perceived workload.

Qualitative data from open-ended surveys supports the argument that Team 1's Checkin WD assumes additional responsibility in terms of managing friendly assets. For example, after trial 24, the SD indicated that "Checkin doing great at controlling airbase and assets – great help to the team" and after trial 38, the SD indicated that "Checkin contributing much to the team by controlling two F18s and being aggressive in her attacks". Qualitative data from Team 2's open-ended surveys do not reveal any such strategy.

From a quantitative perspective, Team 1's qualitative shift in strategy is apparent. Referring to Figure 5.3, about half-way through the trials (around trial 22; intermediate trial period) there appears to be a positive step-function in the number of prime targets eliminated during centralized conditions. This increase in number of assets eliminated is most likely due to the Checkin WD elimination of additional ground targets. Similarly, referring to Figure 5.1, about half-way through trials (around trial 22; intermediate trial period) there appears to be a positive step-function in the number of losses due to enemy attack during centralized conditions. According to experimenter observation, initially Team 1's Checkin WD had trouble keeping F18s in the air according to significant positive micro-level trends in the number of assets lost to enemy attack (intermediate: $t(43) = 2.53$, $p < .05$; later: $t(43) = 2.29$, $p < .05$). This would explain the increase in number of assets lost to enemy attack half-way through the experiment. Finally, when referring to Figure 5.6, it appears that Team 2's launches and transfers mirror each other across trials. In addition, for Team 2, about 92 percent of the variance in transfers is associated with launches (and visa versa; see Table 5.4). Thus, Team 2's Checkin WD is consistently launching and then transferring assets to other operators (as opposed to managing those assets herself). In comparison to Team 2, it appears that Team 1's launches remain relatively constant (see section on macro-structure), however, a significant negative trend is revealed for transfers – especially, half-way through the experiment (see Figures 5.5). In addition, only about 18 percent of the variance in transfers is associated with launches (and visa versa; see Table 5.3). Consequently, it appears that Team 1's Checkin WD is consistently launching similar numbers of assets across trials, however, they are transferring those assets to other operators less frequently toward the second-half of the experiment (i.e., personally managing those assets).

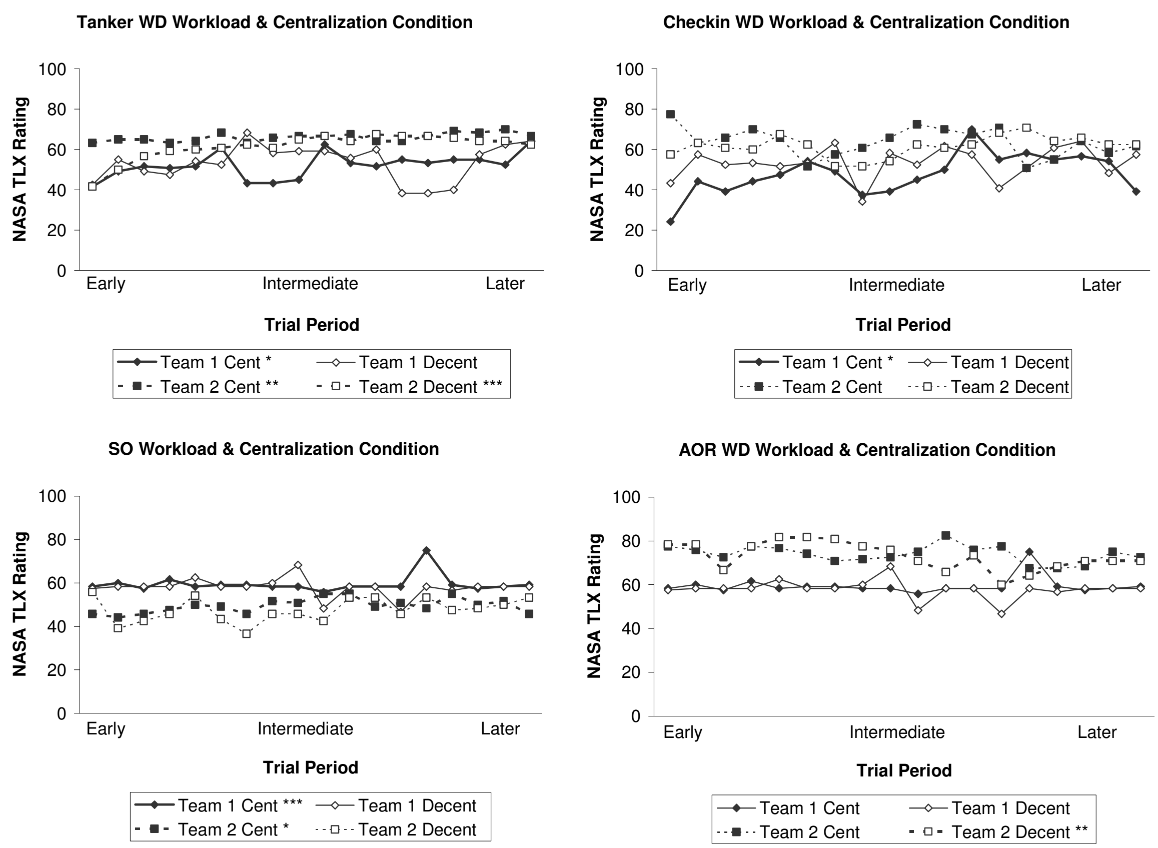


Figure 5.12. Teams 1 and 2: WD's workload by centralization condition.

Although, process- and outcome-related performance data reveal changes in Team 1's performance around half way through the experiment, one would also expect changes in Team 1's Checkin WDs perceived workload around half way through the experiment if they were, indeed, managing more assets and assuming additional responsibilities. Referring to Figure 5.12, during centralized conditions, shortly after half way through the experiment, there is a sharp increase in the Checkin WDs perceived workload. Thus, it appears that Team 1's Checkin WD is learning how to cope (after the high workload spike, perceived workload appears to level off for the Checkin WD) with the additional responsibility associated with controlling additional friendly assets for close-air support and to eliminate ground targets.

The above evidence reveals a qualitative shift in Team 1's performance across trials. Specifically, Checkin WD's management of assets during the second-half of the experiment reveals itself through global variable patterns in performance measures. Although, we expected to discover a greater number of global variable patterns across both Teams' quantitative and qualitative data, we believe that discovering the single qualitative shift in strategy detailed above is a step in the right direction toward understanding how teams dynamically cope with complex situations. Below, qualitative data reveal specific adaptive strategies Teams employed to cope with dynamic and complex scenarios.

Adaptive strategies. Open-ended surveys completed by individuals and Teams reveal specific adaptive strategies discovered and employed by Teams to cope with mission scenarios. One characteristic feature of these strategies involved asset clustering to compensate for asset deficiencies and exploitation of asset capabilities. A second characteristic feature of these strategies involved the transfer of primary responsibilities among operators. Although, above, a qualitative shift in strategy was discussed in terms of transferring elements of Team 1's AOR WD's role to the Checkin WD, further, qualitative evidence supports transfers of responsibility among other operators. A third characteristic feature involves adapting mission priorities to the constraints of the enemy AOR – specifically, by prioritizing specific assets for time-critical attack.

Both Teams learned to cluster assets together to exploit particular capabilities of assets and compensate for asset vulnerabilities. Thus, bombers are capable of eliminating up to four ground targets on a single restocking – however, they do not have any air-to-air attack capabilities. Similarly, although the UAV has the capability of sensing ground targets within a wide range and tankers have the capacity to refuel and restock friendly assets, neither has the ability to defend against enemy air attack. Finally, despite the F18s ability to eliminate up to four air targets, a maximum capacity of one air-ground attack and limited ground sensing facilities makes them vulnerable to SAM sites and limits ground targeting.

The UAV (SO operated) was capable of traversing the AOR in order to detect the location of enemy ground targets. Although, UAVs were capable of 'seeing' ground activity (whereas, other assets did not possess similar capabilities), they could not detect enemy *air* activity that could destroy UAV assets. Thus, both teams learned to pair F18s with the UAV (the AOR WD paired up with the SO) to protect the UAV from enemy air attack. For example, after trial 11, Team 1's Checkin WD commented that the "UAV staying next to tanker with F18s support works well to keep UAV in air". Similarly, after trial 48, the SD commented on Team 2's consistent protection of UAVs, "AOR does a good job watching out for SO, e.g., although out of ammo, he stayed with SO so he could warn him of air enemies".

Both Teams learned to cluster assets together to exploit restocking and refueling capabilities of the tanker and the protection offered by the F18s. Tanker WDs had the responsibility of restocking and refueling all friendly assets throughout the AOR. The Tanker WDs were only allotted three tanker aircraft (not equipped with arms) to accomplish this role. During each mission scenario, fighter and bomber assets were distributed throughout the AOR, which was covered in enemy aircraft and mobile SAM sites. Thus, moving tanker assets around the AOR in order to restock and/or refuel friendly assets was contingent upon safe passage, which was rare. Consequently, each team decided to group their tanker aircraft with fighters and/or bombers to ensure that assets low on fuel/arms had supplies readily available and tanker assets had adequate defenses. Team 1 employed two asset clusters, each consisting of a bomber, F18, tanker and UAV (experimenter observation). For example, after trial 13, Team 1's AOR WD commented, "…worked much better as two teams…" and after trial 14, AOR WD commented, "working as two separate teams works much more efficiently". Similarly, after trial 24, Team 1 commented, "…works well splitting into two attack teams and covering opposite sides, will continue with that strategy. Restocking and refueling works well with both teams." Additionally, in terms of restocking and refueling, according to Team 1's Checkin WD after trial 37, "Tanker and AOR partnered and were able to continually restock F18s so that the F18 could continue to strike ground targets" and after trial 37, Team 1 commented, "better teamwork using Tanker to restock and refuel immediately works well." On the other hand, Team 2 employed one asset cluster (experimenter observation). For example, after trial 34, Team 2's AOR WD commented, "moving the tanker up to meet the fighter and bomber group for restocking and refueling helped".

A second characteristic of these strategies, alluded to above and apparent in operator comments, involved adapting operator roles. Prior to engaging in missions, both Teams' members were given primary responsibilities. As mentioned above, the AOR WD was primarily responsible for all fighters and bombers within the AOR; the Checkin WD was responsible for launching and transferring all assets into the AOR; and the Tanker WD was responsible for all tankers, i.e., restocking and refueling all assets. As teams engaged in mission scenarios, they learned to transfer their responsibilities to other operators. This adaptive strategy is clearly apparent in open-ended survey comments. For example, after trial 38, the SD comments that "all team [1] members doing an amazing job…Tanker and AOR doing well at hitting ground targets; Checkin doing great at controlling airbase and assets, great help to the team" and after trial 41, SD commented that Team 1's "Checkin doing a great job at controlling two F18s and providing air support for Tanker with his bombers and SO. Tanker is observant of what's going on with his teammates and does a good job alerting them to their fuel status in addition to making several ground attacks". In terms of Team 2, after trial 8, SD commented, "Tanker is doing well at attacks with F18s, controlling multiple F18s and dividing attention over entire AOR". Similarly, after trial 29, Team 2's AOR WD commented, "Tanker is great at multi-tasking both refueling and bombing". Thus, it appears that both Teams learned how to transfer roles and responsibilities to cope with dynamic situation constraints.

Environmental contingencies promoted a third characteristic strategy transformation across trials for both Teams that included re-configuring mission priorities. First, both teams established goals to *avoid* enemy attack by discovering consistent patterns in the environment that were believed to be linked to teams' behavior. Both teams noticed that at various times during missions, enemy aircraft 'launched' *en mass* from enemy air bases. Teams discovered that by destroying enemy air bases early enough, the number of enemy aircraft in the AOR would be greatly diminished. For example, after trial 2, Team 1 comments that they should "focus on airbases more in the start to decrease enemy fire and allow access to priority targets" and after trial 15, Team 2's AOR WD commented, "although air bases were not high on the priority list, we set those at a pretty high priority in order to disable enemy's capability to launch bogeys. Then, we attacked higher priority targets along the way".

A second re-configuration of priorities occurred in response to enemy missile launches from missed silo launch sites. Specifically, Teams discovered that during the last minute of each fifteen-minute trial, a series of theater ballistic missiles (TBMs) would be launched, destroying most of a team's assets and prematurely ending their mission. When teams discovered that destroying all missile launch sites would eliminate the launch of TBMs, they formulated strategies for eliminating missile launch sites as early as possible. For example, after trial 8, the SD commented that "missiles destroy too many assets in the end. Has the possible effect of always making silos the top priority" and after trial 19, Team 1 expressed "relief that all silos and all airbases were destroyed". Similarly, after trial 16, Team 2's SO commented, "destroying silos and air bases greatly reduces enemy attacks," and after trial 38, Team 2's AOR WD comments, "it seems that focusing on taking out silos and airbases is a good strategy".

Summary. It appears that both Teams learned several adaptive strategies for coping with mission demands. Qualitative evidence derived from open-ended surveys suggests that both Teams learned to cluster their assets to exploit capabilities and support vulnerabilities; transfer mission roles and responsibilities to more effectively meet mission objectives; and re-prioritize targeting (i.e., enemy airbases and silo launch sites) based on the impact of air enemies and theater ballistic missiles. In the next section, both qualitative and quantitative evidence are discussed in relation to specific strategies Teams employed for utilizing communication technologies. Specifically, how Teams utilized radio, chat, and virtual whiteboard technology depended on the constraints of tasks and degrees of freedom of the communication technology.

Strategies for communication technology use. During the experiment, both Teams were provided radio, chat, and virtual whiteboard technologies to communicate through. Agents were free to decide which medium to utilize for any specific situation. How agents utilized each communication medium ultimately depended on the constraints of the task. Thus, for tasks that required agents to remember specific information, such as target locations that the SO communicated to WDs, both teams used the virtual whiteboard (experimenter observation). For example, after trial 43, Team 2 commented, "SO did well communicating where targets are and used the whiteboard effectively". To be sure, the bulk of virtual whiteboard use was attributed to the SO (see Figure 5.13). For repetitive tasks that required 'yes' or 'no' responses, such as having the SD respond to (radio) permission requests from WDs, the chat medium was preferred by Team 1. In terms of comments related to chat usage, Team 1 suggest after trial 2 that "…SD to use IM so to increase speed of communication" and, after trial 3 "all [members of Team 1] agreed SD should continue to use IM". Specifically, archived chat data (which, could not be partitioned by Team) indicate that 1406 out of 2055 responses from the SD to both teams were 'yes' responses (there were 2 'no' responses; see below on study limitations). The majority of remaining chats consisted of off-topic banter, indicating that the chat tool was not extensively utilized by WD to cope with mission scenarios.

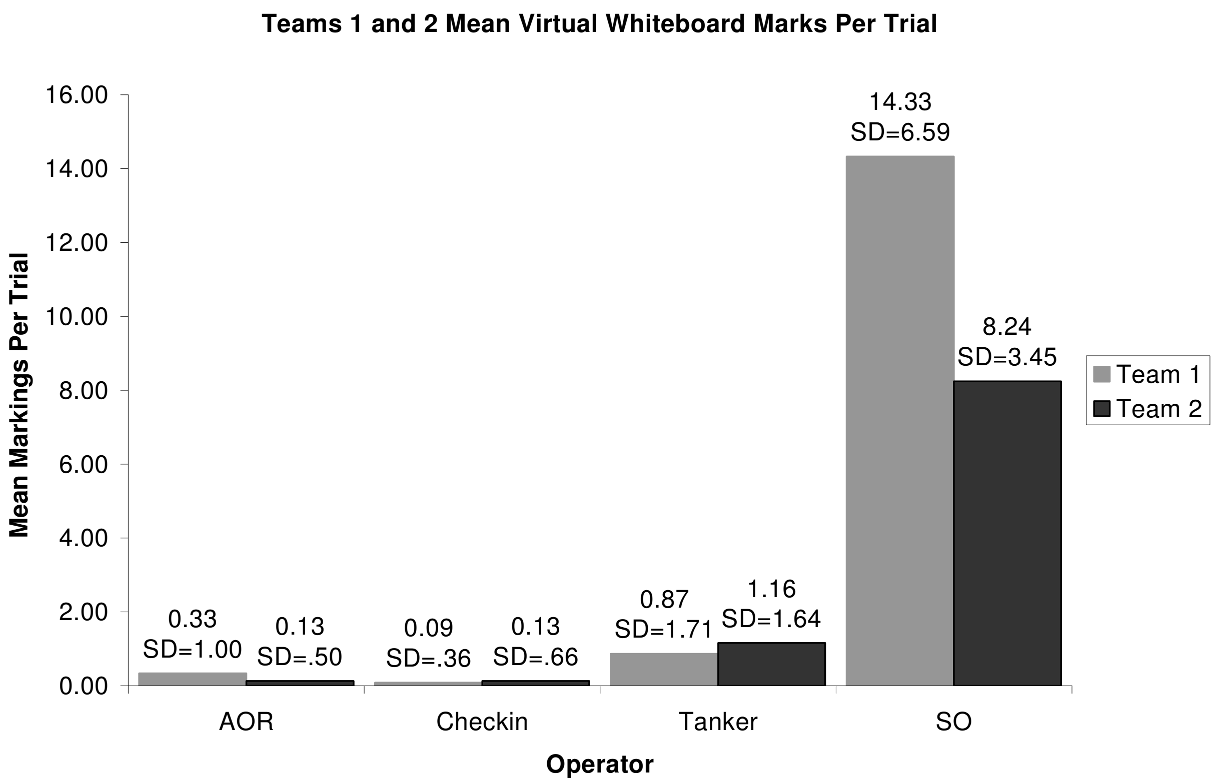


Figure 5.13. Teams 1 and 2: means and standard deviations for virtual whiteboard markings for each operator, per mission.

In contrast to chat and virtual whiteboard usage, it is clear that both teams primarily utilized the radio to communicate through mission scenarios. Although, the virtual whiteboard was utilized by both SOs to mark targets on the tactical display for WDs, the virtual whiteboard is limited by the few symbols available to convey information. Additionally, operators commented on the virtual whiteboard clutter that emerged on the tactical display. For example, after trial 10, the SD commented, "the whiteboard gets cluttered at times occluding the targets. This makes it difficult to determine if sensor rings are in range, if civilians are close, or to even verify where a target is."

On the other hand, the chat tool primarily was utilized by the SD to send confirmation texts to WDs – the WDs did not utilize the chat modality to communicate with each other. Perhaps, the utilization of the radio over the chat modality has something to do with Wickens' multiple resource theory (1984). Specifically, Wickens proposes that individuals possess separate, limited pools of mental resources for spatial and verbal information processing and that they utilize these resources independently or jointly depending on the demands of the information processing components that comprise a task. According to Wickens, due to the limitations of cognitive resources, an individual cannot optimally process two or more competing visual and/or auditory tasks at the same time (1984). Additionally, Wickens (2002) argues that time-sharing between tasks that involve different modalities is more beneficial than intra-modal time-sharing. During the present study, operators' visual resources were required to vigilantly monitor the situation display and to type and read chat messages during mission scenarios. Therefore, operators may have preferred to 'off-load' information exchange to the radio/auditory modality.

In the above sections strategy development and employment was discussed in terms of interdependencies among agents (i.e., transferring roles and responsibilities and asset clustering) and target prioritization (i.e., missile launch silos and enemy air bases).

In the next section, the relationship between agent beliefs, outcome-related performance, and constraint condition will be explored. Additionally, how correlations among agents beliefs (i.e., situation awareness) corresponds to outcome-related performance will be examined.

Agent Beliefs

Sarter and Woods define situation awareness as, "the accessibility of a comprehensive and coherent situation representation which is continuously being updated in accordance with the results of recurrent situation assessments" (1991; p. 52). Endsley and colleagues (2003) define *team* situation awareness (i.e., shared SA) as the degree to which team members have the same SA in a given situation. The authors propose that the optimal team SA would entail congruent and accurate SA among team members – the accuracy of team SA is contingent upon the accuracy of each team member's SA. The authors further argue that communication plays the key role of reducing potential discrepancies between individual's SA.

Based on the above definition of team situation awareness, both Teams' *beliefs* concerning outcome-related performance (i.e., number of ground targets eliminated and number assets lost) were related to *actual* outcome-related performance across trials (see Figure 5.14) to determine SA 'accuracy'. Statistical analyses reveal significant differences between belief and actual outcome-related performance measures for both teams. Specifically, analyses indicate that both Teams consistently underestimated the number of targets eliminated and the number of assets lost during each trial [Team 1: Ground Targets: (Actual: $M = 9.27$, $SD = 3.62$; Belief: $M = 7.15$, $SD = 1.66$) $t(44) = 5.80$, $p < .05$; Asset Losses (Actual: $M = 14.18$, $SD = 3.87$; Belief: $M = 12.12$, $SD = 1.79$) $t(44)$

= 4.11, $p < .05$] and [Team 2: Ground Targets (Actual: $M = 9.67$, $SD = 3.04$; Belief: $M = 6.28$, $SD = 1.83$) $t(44) = 12.71$, $p < .05$; Asset Losses (Actual: $M = 15.8$, $SD = 4.17$; Belief: $M = 10.92$, $SD = 1.50$) $t(44) = 8.94$, $p < .05$]. Thus, agents were consistently inaccurate across all trials, i.e., agents had 'low SA'.

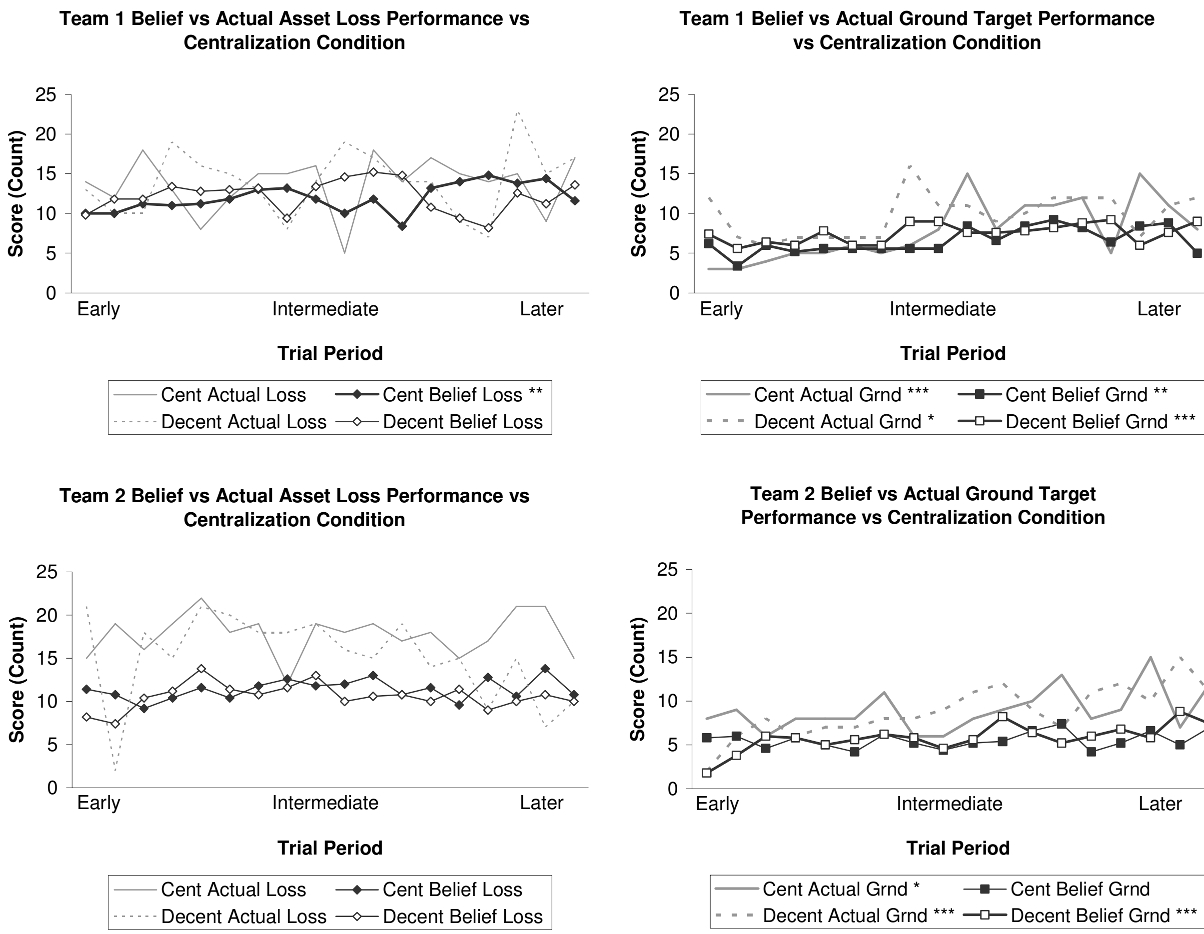


Figure 5.14. Teams 1 and 2: across trial periods, average team member beliefs concerning outcome-related performance compared to actual outcome-related performance by centralization condition.

A second component of the above definition of situation awareness is the degree of similarity between operators' and Teams' beliefs concerning mission scenarios. Specifically, determining discrepancies between operator and Team beliefs reveals who is 'out of touch' with the Team. In terms of the qualitative shift in performance discussed earlier, we expected that Team 1's Checkin WD's beliefs to exhibit a stronger correlation with Team 1's beliefs than Team 2's Checkin WD's belief in relation to Team 2's beliefs. In other words, we expected that Team 2's Checkin WD would be more 'out of touch' with their Team's beliefs relative to Team 1's Checkin WD because they were not actively taking on other roles and they were not required to consistently pay attention to what went on during mission scenarios. Each operator's beliefs were correlated with Teams' beliefs concerning the number of ground targets eliminated and the number of friendly assets lost (see Table 5.5). Results indicate that, in terms of ground targets eliminated, Team 2's operators exhibited stronger correlations with the Teams' beliefs than Team 1's operators. In particular, contrary to what we expected, Team 2's Checkin WD's beliefs exhibited a stronger correlation with the Teams' beliefs than Team 1's Checkin WD. Thus, Team 2's operators - including the Checkin WD - had higher team 'SA' than Team 1's operators.

Table 5.5

Pearson-r Values for Teams 1 and 2: Relationship Between Operators' and Teams' Beliefs (Team 'SA')

Team	Operator	Ground Targets	Friendly Asset Losses
1	AOR WD	0.32 **	0.12
1	Checkin WD	0.66 ***	0.42 ***
1	Tanker WD	0.60 ***	0.47 ***
1	SO	0.42 ***	0.35 ***
2	AOR WD	0.85 ***	0.33 ***
2	Checkin WD	0.86 ***	0.73 ***
2	Tanker WD	0.78 ***	0.65 ***
2	SO	0.83 ***	0.41 ***

** $p < .01$; *** $p < .001$

Summary. Results from the present study do not support a relationship between agent accuracy, team performance, or congruency among agent beliefs. Although, we expected a positive trend in agent accuracy across trials, results indicate that both Teams were consistently inaccurate. Additionally, specific expectations concerning Team 'SA' and differences in mission engagement among Checkin WDs were not supported – the Checkin WD that was most engaged in mission scenarios exhibited a weaker correlation between their beliefs and their Team's beliefs compared to the Checkin WD that was less engaged in mission scenarios.

Summary of Teams' Characteristics

Teams 1 and 2 exhibited different characteristics across experimental trials. Relative to Team 1 that evolved aggressive strategies for coping with mission scenarios, Team 2 was more conservative. Specifically, Team 2 deployed a single cluster of assets across mission scenarios versus Team 1's dual asset clusters; Team 2's Checkin WD did not assume other operator's roles; and Team 2's operator's beliefs about mission scenarios appear to be more in-line with their Teams' beliefs than Team 1's operator's beliefs. Thus, Team 2 did not attempt potentially risky strategies and operators were more 'in touch' with the Team than Team 1 and its operators.

Although, both Teams experienced increased frustration when coping with mission scenarios under centralized organizational constraints, Team 2 appears to have experienced a significant perceived workload increase during centralized condition trials. However, mixed results concerning organizational centralization do not support strong conclusions about specific effects on either Team. Ultimately, across trials, both Teams learned how to cope with dynamic and complex mission scenarios by evolving specific strategies, such as prioritizing the elimination of enemy air bases and missile launch silo sites.

CHAPTER 6: CONCLUSION

The friendly fire accident discussed in the introduction (see Chapter 1) reveals that system failures occur despite typical agent behavior and theoretical predictions. Scott Snook (2000), whom explores the dynamics of the friendly fire incident, argues that one cannot focus solely on the technological complexity of (e.g., military) work domains, as researchers within the Normal Accident tradition (e.g., Perrow, 1999) focus. Instead, one must incorporate the perspective of High Reliability Organization researchers (e.g., Weick and Sutcliffe 2001) that focus on uncovering the underlying behavioral and organizational dynamics inherent to the military work domain that can contribute to Normal Accidents. Snook argues that the interrelationship between social and technological dimensions coupled with dynamic, or continuously changing situations creates work domains that are highly complex and that require reliable and adaptive control solutions.

In the following sections, a definition of *complexity* will be reiterated (see Chapter 2), specifically, in terms of complex work domains. This will be followed by a re-consideration of the possibility and problem of *control* in complex work domains, such as AWACS BMC2 (see Chapter 2). Finally, the empirical study elaborated above (see Chapter 4 and Chapter 5) will be discussed in terms of implications, limitations, and directions for future work.

Complexity and Control

Complexity, as defined above, emerges from two facets, dimensionality (i.e., the number of components or elements within a system) and coupling (i.e., slack or buffer between components). For example, controlled experiments represent relatively low dimensional, tightly coupled environments. Experimental phenomena are deliberately simplified and the tight coupling between stimuli and responses ensures that reliable inferences can be made. Conversely, work environments such as the Air Operations Center, AWACS BMC2, or operating rooms represent complex domains characterized by high dimensionality and relatively loose coupling. For example, in the Air Operations Center, diverse agents from different organizations with different technologies, must work together both internally and externally to maintain control of an active battlespace. Whereas observations and descriptions of organizations such as Air Operations centers and operating rooms suggest that stable control is possible in complex work domains, it is difficult to generalize from these observations without considering fundamental aspects of control systems.

As discussed in Chapter 2, *control* is a relation of constraint of one element by another (e.g., a pilot controls an aircraft). Control systems, such as AWACS BMC2 or accounting firms, can be differentiated into control *problems* and control *solutions*, wherein the control problem refers to the computations demands of a work domain and the control solution refers to the organizational strategies for meeting those demands. According to the *law of requisite variety*, the variety of any control solution must at least match that of the control problem. Thus, in work domains such as assembly lines or bricklaying, a single, optimal control solution can be developed to meet the requisite variety of the work domain. However, the demands or variety of many complex work domains require control solutions that can meet the demands of a variety of dynamic and complex situations.

Often, the variety exhibited by a control problem is massive and/or variable and the control solution does not have enough variety to match it. Consider the number of cells in the nervous system, and the number of muscles and joints throughout the human body. How does the system coordinate purposeful behavior considering all of the independent variables? In other words, how does the system maintain control over all of its components, such that it can produce coordinated action? One solution to this problem is to ascribe control to a centralized 'program' that manages all of the many independent variables in a system. This is the classical approach to motor control. A fundamental problem with this approach is that the massive number of degrees of freedom that have to be managed cannot be computationally realized. In other words, it is impossible for the brain to actively attend to and manage all of the variables required for coordinated action. A second solution is to describe control as a condition that emerges from specialized self-organizing functions that capitalize on the demands of specific situations. This question as to how control over a multitude of independent variables is maintained was initially deliberated by the motor control scientist Nicolai Bernstein (1967), who presents it as the degrees of freedom (i.e., independent variable) problem.

Bernstein attempts to resolve the degrees of freedom problem from the perspective of motor control by arguing that the motor system simplifies things by *reducing* the degrees of freedom by constraining them to act together. Specifically, the process of coordination can be seen as the progressive mastery of multiple degrees of freedom. According to Bernstein (1967), when an agent is first exposed to a motor task, degrees of freedom are 'frozen', thus reducing the number of control constraints.

Experimenting with fewer degrees of freedom affords a smaller number of directions of stability that guides the coordination of additional degrees of freedom. For example, when first learning to kick a ball, correctly timing when to flex and extend the hip, knee, and ankle, and performing the correct range of motion to move each joint is difficult. To 'solve' this degrees of freedom problem the learner will 'freeze' his or her knee and ankle and only change the angle of the hip. This strategy of movement organization results in a straight leg kick, which is easier for the novice to perform, but does not allow the control of the movements needed for a skilled kick. With practice the performer will begin to 'release' the degrees of freedom by moving the hip joint independently of the knee-joint, and moving the knee-joint independently of the ankle-joint. Thus, degrees of freedom are progressively released and incorporated into larger functional units called *coordinative structures* (i.e,. functional assemblies of muscles, strategies, or behaviors for specific patterns of coordination; Kugler et al., 1980). It is important to note that the skilled 'kicker' or soccer player locks degrees of freedom out in a 'smart' way. Specifically, the skilled kicker finds the strategy that allows coordination and control that satisfies the particular domain constraints, as opposed to performing movements in a pre-programmed rote or 'dumb' way. Runeson (1977) calls specialized organizations (e.g., a skilled soccer player) that capitalize on the unique features of situations and tasks, *Smart Instruments*.

The abovementioned degrees of freedom problem also is faced in real-world work domains. For example, in order for the U.S. Air Force to carry out a variety of critical missions, specifically assigned forces must be organized through planning and directing operations. This is known as air battle management (see Chapter 4). The Air Tasking

Order, which is the published order that directs all air operations (i.e., assigning mission tasking and detailing specific strategic targets) is transmitted to the AWACS, which commands and control friendly assets in order to accomplish the mission objectives outlined in the Air Tasking Order. In other words, the AWACS must actively manage all fighter, bomber, refueling tankers, and sensor assets (e.g., UAVs) within a specified area of responsibility in order to accomplish specific military objectives.

Weapons Directors onboard the AWACS are responsible for managing the variety of friendly assets in order to accomplish mission objectives. Weapons Directors and the SD work as a team to provide friendly forces with a ‘big picture’ of the battle-space; assisting in finding, identifying, and destroying enemy targets, keeping track of friendly assets, and coordinating air refueling. The AWACS WDs must coordinate the elimination of enemy targets, asset re-fueling with tanker aircraft, and the close-air support (i.e., protection) of friendly assets. Additionally, in the AWACS BMC2 domain, like other military domains, the control structure varies by platform. In a real-world AWACS domain, the SD may be the only military officer among enlisted WDs. Therefore, mission-specific actions must be approved by the SD; i.e., the AWACS unit is characterized by centralization of command. In other circumstances, the WDs may be officers and the SD may afford them the freedom to commit actions without approval; i.e., in these cases, command is de-centralized. As discussed above, there are two ways of managing complexity: through centralization and a command program or through de-centralization and emergent behavior. Thus, an interesting research question is, How does each proposed solution effect the performance of teams attempting to manage complex mission situations? This question concerning AWACS BMC2 team’s management of variety under varying degrees of organizational centralization was explored through the present study.

As mentioned above, organizations survive or maintain stability by constraining the degrees of freedom intrinsic to a specific environment (and, visa versa). Indeed, the management of variety is a general problem for all organizations. Through the present study, both Teams evolved coordinative structures (i.e., asset clusters) to cope with multiple friendly assets and complex and dynamic mission scenarios. Initially, Team 1 froze degrees of freedom (i.e., developed asset clusters) to cope with the variety of friendly assets that needed to be coordinated to meet mission demands. However, after evolving a two asset cluster strategy, degrees of freedom needed to be 'released' to cope with increased coordination demands. Thus, Team 1's coordinative structure evolved to meet the demands of mission scenarios by expanding the Checkin WDs role. Conversely, Team 2 froze degrees of freedom by constraining assets into one cluster. Perhaps, by utilizing a single asset cluster, Team 2's coordination demands did not require the release of additional degrees of freedom; the Checkin WD may not have been required to provide additional assistance. Accordingly, both Teams actively adjusted degrees of freedom to the demands of emerging situations. In other words, both Teams moved toward *smart solutions*.

As discussed earlier, specialized organizations, such as AWACS BMC2 teams, that capitalize on the unique features of situations and tasks (i.e., modulate degrees of freedom based on situational demands) are called *smart instruments* (Runeson, 1977). To be sure, a fundamental characteristic of all life forms is compatibility with prevailing constraints. In other words, (natural) organizations survive or maintain stability by constraining the degrees of freedom intrinsic to a specific environment (and, visa versa). Conceptualizing skilled teams as *smart instruments* is a new way of thinking about team performance through complex domains. By revealing how teams managed degrees of freedom through a simulated AWACS BMC2 domain under varying centralization constraints, the present study develops a foundation for further investigations into coordinated activity.

Although, qualitative and quantitative data patterns from the present study revealed the self-organization of two teams working through simulated AWACS BMC2 scenarios, there were some methodological limitations. The next sections will highlight specific limitations of the present study and then discuss future directions for related research.

Study Limitations

The present study suffered a number of limitations. First, the number of teams involved in the study was limited to two. If more teams were involved in the study, a greater number of statistical analyses with greater power to detect significant effects within *and* between teams could have been employed. Indeed, two teams did not offer the requisite statistical degrees of freedom to conduct between team analyses. However, the goal of the present research was to understand the dynamics of individual teams as opposed to increasing power across teams.

Second, the present study did not involve strong tests of hypotheses. Through controlled experimentation, an independent variable is the only factor that varies systematically whereas all confounding variables are eliminated. Additionally, through controlled experimentation, a dependent variable 'validly' represents the phenomenon under study and is measured ‘accurately’. These tight constraints imposed through controlled experiments might support testing a specific theory or help make particular behavioral predictions; however, a major objective of this study was to observe the emergence of complex global patterns in team behavior through a simulated BMC2 domain. This goal precluded the use of a completely controlled laboratory environment as we did not want to overly constrain the behavioral possibilities of Teams. Thus, the present study relied on observations of the performance variables of Teams under study, rather than manipulating a few variables (although, organizational centralization was manipulated). Unfortunately, the correlation among performance variables reduces the reliability of the present study relative to what could be concluded if a controlled experiment were performed.

A third limitation of the present study is that the centralization condition did not present the same centralization constraints present in real-world AWACS BMC2 environments. In particular, the centralization condition turned out to be a minor temporal constraint that Teams worked around with minimal effort (albeit, with some frustration). Additionally, during the present study, the SD was not very involved in mission scenarios - the majority of the SD’s time was spent responding ‘yes’ to WD requests. The centralization condition could have been more representative of real-world situations if it involved a greater degree of SD involvement. To be sure, in real-world AWACS environments, the SD actively participates in BMC2 missions – especially, during pre-emptive strike scenarios! The active involvement of the SD as a centralizing constraint should create the type of bottleneck one would expect in real-world situations, wherein information must pass through a single, centralized ‘node’ prior to becoming available.

A fourth limitation of the present study is related to the limitations of surveys. Specifically, surveys tend to be weak on validity and strong on reliability. The post-hoc and artificial nature of surveys puts a strain on validity because agents’ beliefs are hard to understand *after* an experience and in terms of ratings on a scale. To counter the latter problem, surveys for the present study included open-ended questions that afforded more degrees of freedom for subjects to elaborate on responses. Conversely, surveys are reliable in that they present subjects with a standardized stimulus, thus eliminating unreliability in a researcher’s observations. Careful wording and empirical validation can enhance the reliability and validity of surveys. However, only the NASA TLX has undergone significant empirical validation (Hart & Staveland, 1988), whereas other individual and team scale and open-ended items relating to performance were not empirically validated.

A fifth limitation of the present study concerns ecological validity – does the STE utilized in the present study adequately represent the dynamics and complexity present in actual AWACS BMC2 domains? The answer is certainly, ‘no’ – but, the STE afforded a non-reductionistic platform for observing team dynamics and self-organization. To be sure, the STE engaged teams in mission scenarios based on real-world situations, which promoted similar types of problem-solving, decision-making, and self-organizing behaviors that one would expect on an actual AWACS. As mentioned in Chapter 4, the STE performs as a research ‘bridge’ between naturalistic studies that are extremely difficult to carry out (especially, on an active AWACS) and controlled laboratory experiments that over-simplify complex phenomena.

Although, the present study suffered several limitations, it provided a framework for understanding team dynamics through a complex domain (see Chapter 4). Indeed, the utilization of a STE with AWACS BMC2 scenarios based on real-world mission constraints offered an excellent platform to observe the self-organization of team behavior in response to continuously changing and challenging situations. Future research, utilizing similar techniques, should focus on the particulars of self-organization and the development of teams/organizations as *smart instruments*.

Future Directions

The principles by which the functional order of a self-organizing systems (e.g., AWACS BMC2 team) achieve dynamic stability provide a non-reductionist framework for understanding how high reliability organizations adapt to situational demands. In particular, the integrative action of an organization/team can not be understood as an additive function of components, but as a relationally evolving organization emerging from the requirements of constitutive parts. Therefore, in order to understand the evolution of 'smart' solutions, future research involving self-organizing systems must focus on the *meaningful* value, action, and information constraints of specific control problems (see Chapter 2). In other words, future research seeking to understand how highly reliable organizations continuously adapt to dynamic situations must study said systems in 'real' (i.e., *in situ*) or synthetic environments that preserve the semantics of the work domain.

As mentioned above and in Chapter 2, the capacity of self-organizing systems (e.g., high reliability organizations such as AWACS BMC2 teams) to adapt – i.e., to develop *smart mechanisms* (Runeson, 1977), is embodied in the functional organization of the control mechanism. Thus, to understand how smart instruments evolve and survive, future research should focus on how agents and subsystems within dynamic organizations communicate and how coupling and de-coupling of organizational components and constraints results in the loss or gain of adaptive fitness. In other words, future research should focus on how organizations self-organize around domain constraints and modulate ('freeze' or 'release') degrees of freedom (i.e., variety) to meet the demands of dynamic and complex situations. For example, how do teams from different military branches (e.g., air force, marines) that manage a variety of friendly assets (e.g., tanks, aircraft), working under de-centralized conditions, self-organize around specific problematic situations – e.g., a defensive maneuver or time sensitive targeting? How can particular information displays support effective self-organization? Does the number of components affect the development of smart solutions? If so, how?

The self-organization of complex and divergent populations, such as a military C2 team, can be difficult and time consuming to emerge (Seel, 2001). Future research should explore specific organizational conditions that could facilitate self-organization in certain complex domains. For example, taking off where the present study leaves off, the effects of organizational centralization should be studied more closely. From an experimental perspective, during centralization conditions, the SD's responses can be constrained directly or the SD can be remotely located, thereby increasing time lags. During the present study, time lag did not present a significant obstacle to coordination, however, future research should explore the effects of greater amounts of lag on team performance. An additional approach to studying organizational centralization is through promoting and examining self-organizing among AWACS Teams under more complex conditions of SD constraint. For example, the SD can be incorporated in missions as another degree of freedom (e.g., to take on alternative roles), allowing for new team configurations to emerge.

Summary. It should be clear that the organization of behavior is a central concern for science. Indeed, psychologists are interested in how agents (e.g., individuals, teams) purposefully generate behavioral patterns that are tightly coordinated with the environment. This production of stable and adaptive behavior is predicated on the effective coordination of action within the constraints of a dynamic environment. The present study explored the coordinated action of two AWACS BMC2 Teams engaged in a dynamic battlespace. Through an evaluation of both Teams' performance, patterns of behavior were uncovered revealing organizational learning and coordination; self-organizing. It is the author's hope that the results of the present study will contribute to how psychologists and engineers think about, design, and develop socio-technical systems.

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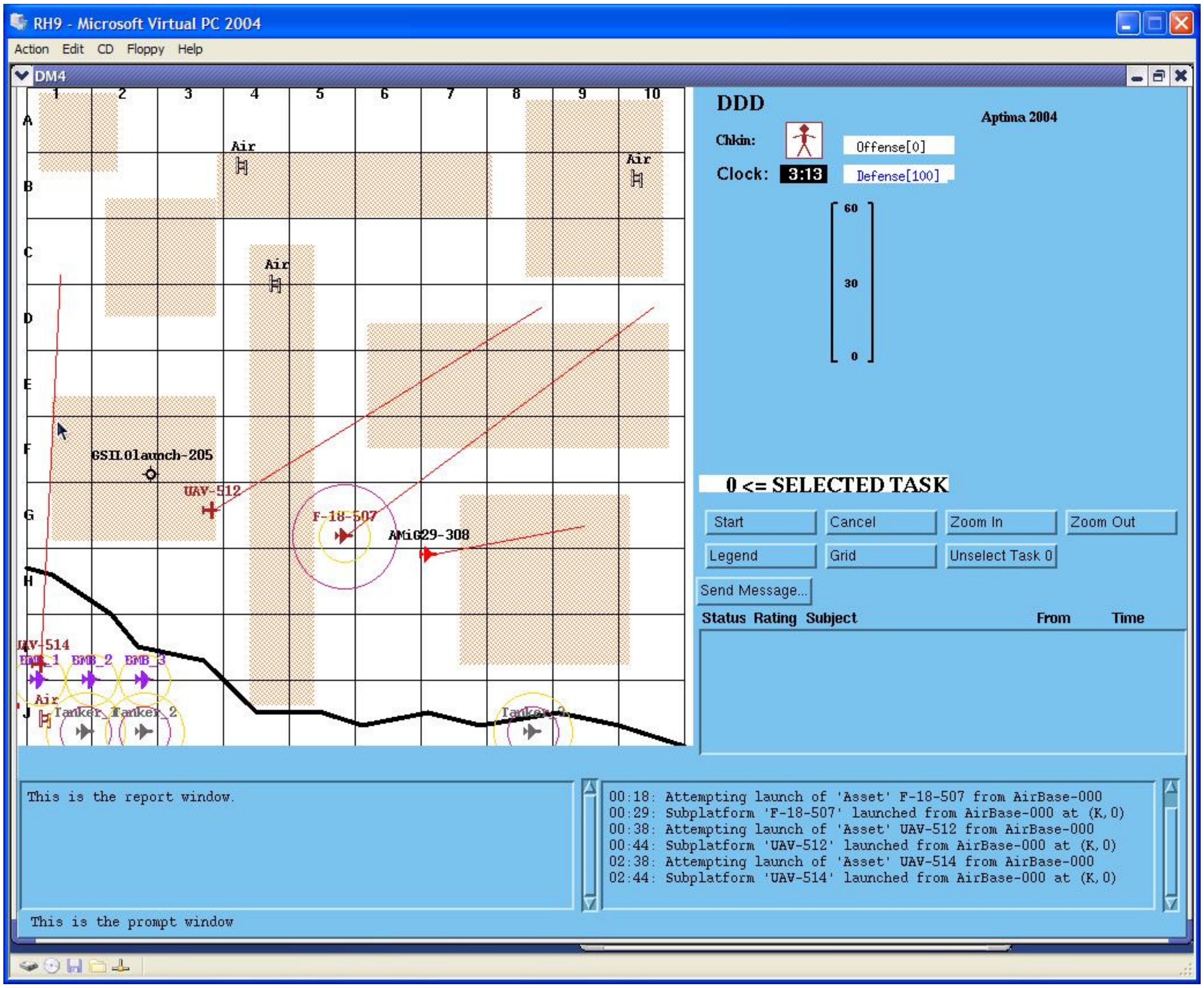
Appendix A



RH9 - Microsoft Virtual PC 2004
Action Edit CD Floppy Help
DM4
DDD
Aptima 2004
Chkin:
Offense[0]
Clock: 3:13
Defense[100]
60
30
0
0 <= SELECTED TASK
Start
Cancel
Zoom In
Zoom Out
Legend
Grid
Unselect Task 0
Send Message...
Status Rating Subject From Time
UAV-512
F-18-507
AMiG29-308
UAV-514
This is the report window.
00:18: Attempting launch of 'Asset' F-18-507 from AirBase-000
00:29: Subplatform 'F-18-507' launched from AirBase-000 at (K,0)
00:38: Attempting launch of 'Asset' UAV-512 from AirBase-000
00:44: Subplatform 'UAV-512' launched from AirBase-000 at (K,0)
02:38: Attempting launch of 'Asset' UAV-514 from AirBase-000
02:44: Subplatform 'UAV-514' launched from AirBase-000 at (K,0)
This is the prompt window

Appendix B

965th Airborne Air Control Squadron

The 965th Airborne Air Control Squadron is an operational unit of Air Combat Command's 552nd Air Control Wing, Tinker Air Force base, Okla.

Mission: The 965th AACS provides responsive employment of E-3 Airborne Warning and Control aircraft for surveillance, warning and control in a variety of tactical, strategic and special mission applications.

Distribution: F

2006-2007

COMPLIANCE WITH THIS PUBLICATION IS MANDATORY

I. Team Members:

1. **Senior Director (SD)**: monitors the WD team, facilitates coordination b/w WDs and generally makes sure mission stays on track. Also, is the officer that the (often enlisted) WDs must get approval through to change plans or take out targets. Many decisions are outside WDs authority. SD must be kept informed of all unplanned events. The SD can provide the function of asking why WDs made the decisions they did and record that info for analysis.
2. **Weapons Director 1: Tanker WD**: Primarily responsible for restocking and refueling of friendly assets and monitors tanker high value assets. Informs the AOR WD when an aircraft leaves tanker and re-enters the AOR, or when something happens with the HVA that is not on the ATO. Also tells Check-in WD when tanker going back to base.
3. **Weapons Director 2: Area of Responsibility (AOR) WD**: Informs the Tanker/HVA WD when an aircraft is coming to a tanker for refueling/restocking, and tells the Check-in WD when an aircraft is leaving the AOR (e.g., going back to base). Primarily responsible for F18 fighters (air-air) and B52 bombers (air-ground)
4. **Weapons Director 3: Check-in WD**: needs to identify and launch any aircraft taking off from the base. Once finished, he 'pushes' (i.e., transfers) the aircraft to the AOR, Tanker/HVA, or sensor operator frequency and tells the appropriate WD that this has happened. The check-in WD also takes control of aircraft that are going back to base
5. **Sensor Operator**: Controls UAV sensor aircraft. Reports observed enemy ground targets to WDs and relays coordinates.

II. Rules:

1. WD3 (Check-in WD) launches all friendly assets (UAV, F18, B52) from base. Assets must be *transferred* to appropriate operator/WD: UAV *to* sensor operator; F18 and B52 *to* WD2 (AOR WD).
2. Team must follow ATO.
3. Each WD has a primary responsibility (as outlined above). However, all WDs are familiar w/ other WDs responsibilities and periodic transfers of responsibility may be required due to scenario demands. WDs can request a transfer of their assets/responsibilities to another WD. Similarly, WDs can request another WDs assets/responsibilities.

III. AOR/Platform Characteristics:

- Enemy targets may be visible to all operators or not. In order to 'see'/detect certain targets, a special platform may be required.
  - Most enemy ground targets will require a UAV to detect their location.
- The destruction of certain targets may require special platforms:
  - *Ground targets* (e.g., missile launch silos) require strike packages (STRK)
    - B52s are equipped w/ 4 STRK packages
    - F18s are equipped w/ 1 STRK package
    - UAVs are equipped w/ 0 STRK packages
    - Tankers are equipped w/ 0 STRK packages
    - The base is equipped w/ 0 STRK packages
  - *Air targets* (e.g., MiGs) require combat air packages (CAPs)
    - B52s are equipped w/ 0 CAP packages
    - F18s are equipped w/ 4 CAP packages
    - UAVs are equipped w/ 0 CAP packages
    - Tankers are equipped w/ 0 CAP packages
    - The base is equipped w/ 0 CAP packages

- Each platform has a predetermined amount of fuel and arms that will need to be replenished by either a tanker or base. Tanker restocking and refueling is a coordinated activity.

<u>Scenario</u>

ATO:

Overview/Background:

For the last decade, tensions have been high on the boarder between Country A and Country B. Country A has accused Country B of developing weapons of mass destruction (i.e., biological weapons) and of crimes against humanity. It is believed that the biological weapons are being stored in secret underground bunkers. Last week, Country B kidnapped two of Country A soldiers. This act provoked outrage throughout Country A.

Mission:

The mission is to preemptively strike Country B and eliminate theater ballistic missile launch sites before they strike Country A; destroy biological weapons manufacturing sites and the secret bunkers that store stockpiles of manufactured weapons of mass destructions.

1. Prepare AOR for sensor, tanker, and bomber aircraft
2. Destroy enemy air bases
3. Destroy communication centers
4. Destroy bridges
5. Defeat enemy air forces
6. Destroy biological weapon manufacturing sites
7. Eliminate/protect HVAs from SAM sites
8. Eliminate WMD bunker storage sites

Rules of Engagement:

Entities and Roles:

- Command
    - Coordinate, monitor, and supervise
    - Utilization of all assets to define a situation
- Battle Management
    - Execute ATO and mission objective through direct tasking and coordination
    - Assure that all tasks are destroyed
    - Maintain a clear picture of all tracks in the AOR
    - Prompt destruction of tasks
- Assessment
    - Rapidly fuse and exploit surveillance and target data
    - Request additional information if necessary
- Surveillance
    - Build accurate picture of the AOR
    - Effective collection of information from all entities in the AOR
- ISR Management
    - Manage ISR constellation
    - Assure no gap in ISR coverage

Tasks by Platform

Fighter Aircraft: based on Airbase in Country A (F18s)

1. Enemy fighter aircraft
2. Enemy ground targets
3. Protect friendly forces
4. Suppress enemy movements

Bomber Aircraft: based in Country A and on Airbase in Country A (B52s)

1. Enemy ground targets
2. Ground based enemy air defenses

3. Enemy air bases

Sensor Aircraft: based on Airbase in Country A (UAVs)

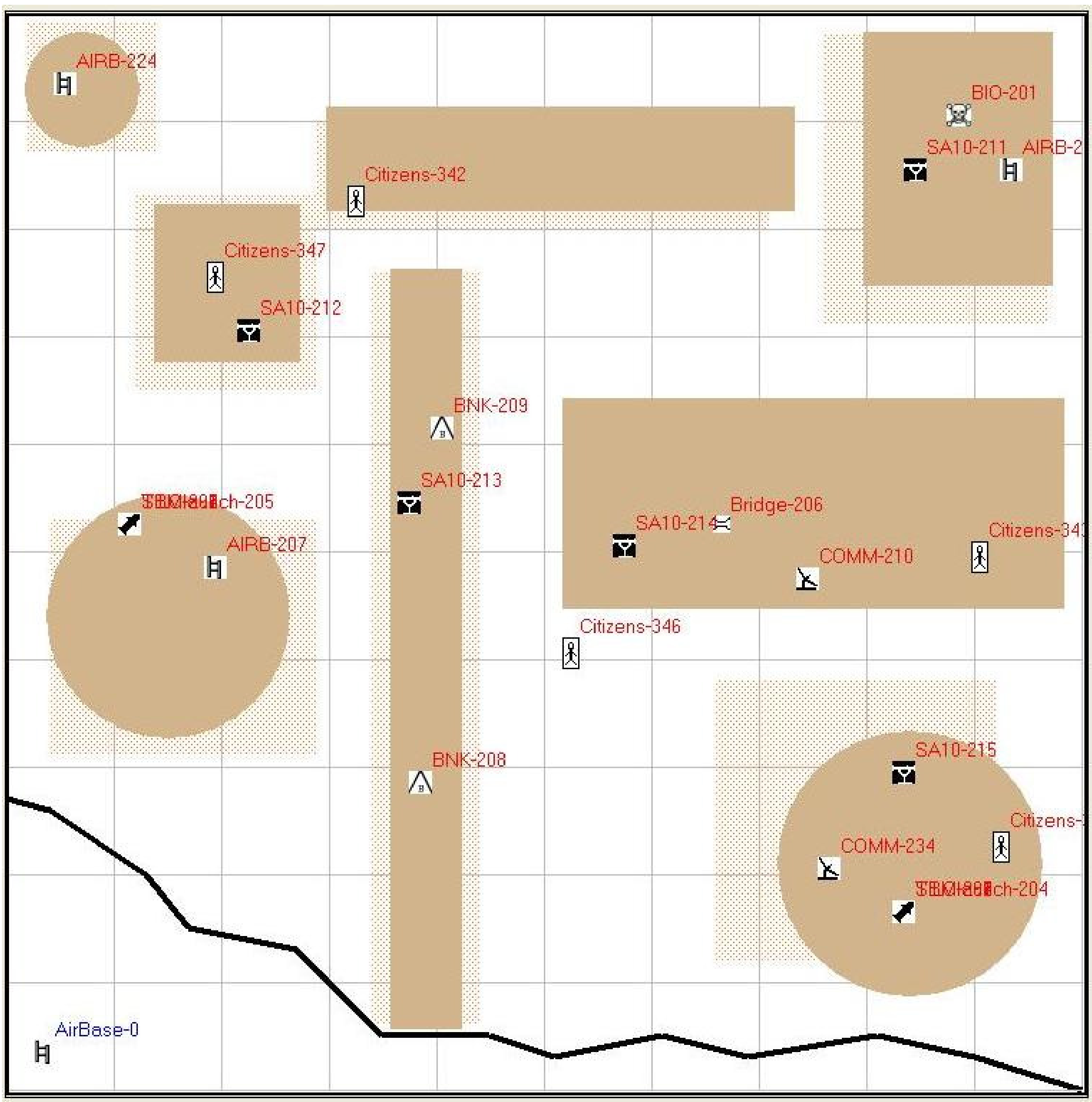
1. Provide ISR (Intelligence, Surveillance, Reconnaissance)
2. Provide coordinate information about enemy ground targets

Tanker Aircraft: based in Country A

1. Provide fuel and arms for friendly assets

Appendix C

965th Airborne Air Control Squadron
INTELLIGENCE BRIEFING



This image was captured over ‘Country B’ at 1400 hrs two weeks ago. Image reliability is unknown.

Appendix D

INDIVIDUAL BELIEF ASSESSMENT PT 1

Instructions: Please, complete the following regarding your name and position

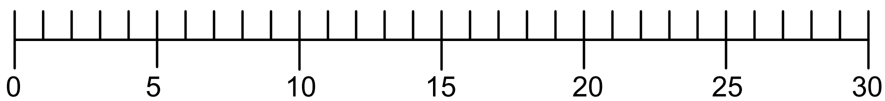
Name:

Position: 1) **AOR WD** 2) **Checkin WD** 3) **Tanker WD** 4) **SO**

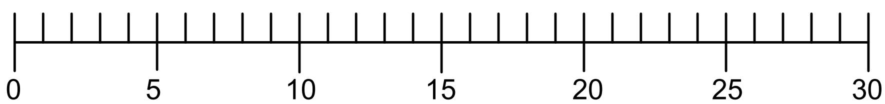
5) **SD**

Instructions: For each of the questions presented below, ***please write the number*** *that matches* YOUR *-or- your* TEAM's *performance for the mission just completed*

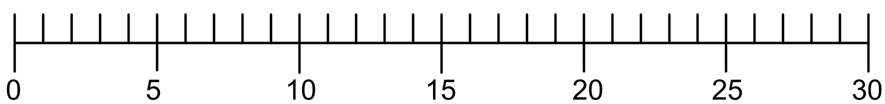
1. *How many ground targets did* **YOU** *destroy during this mission?*



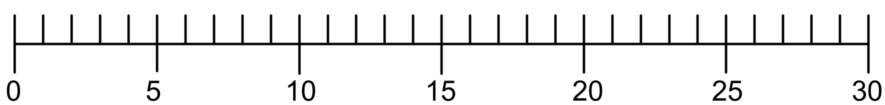
2. *How many friendly assets did* **YOU** *lose during this mission?*



3. *How many ground targets did your* **TEAM** *destroy during this mission?*



4. *How many friendly assets did your* **TEAM** *lose during this mission?*



Instructions: For each of the questions presented below, ***please write the number*** *that matches* YOUR *-or- your* TEAM MEMBER's *performance for the mission just completed. Note: for questions 6, 7, & 8, do* NOT *respond if you are the position being questioned (your performance is assessed in question 5).*

5. *How did* **YOU** *perform during this mission?*

   POOR 1 2 3 4 5 6 7 GOOD

6. *How did* **Checkin WD** *perform during this mission?*

   POOR 1 2 3 4 5 6 7 GOOD

7. *How did* **AOR WD** *perform during this mission?*

   POOR 1 2 3 4 5 6 7 GOOD

8. *How did* **Tanker WD** *perform during this mission?*

   POOR 1 2 3 4 5 6 7 GOOD

9. *How did the* **SO** *perform during this mission?*

   POOR 1 2 3 4 5 6 7 GOOD

10. *How did the* **SD** *perform during this mission?*

    POOR 1 2 3 4 5 6 7 GOOD

11. *How did your* **TEAM** *perform during this mission?*

    POOR 1 2 3 4 5 6 7 GOOD

Instructions: For each of the scales presented below, ***please write the number*** *that matches* **<u>YOUR</u>** *experience with the mission just completed. *Please note that the "Performance" scale goes from "good" on the left to "poor" on the right*

Mental Demand

Low 0 25 50 75 100 **High**

Performance*

Good 0 25 50 75 100 **Poor**

Physical Demand

Low 0 25 50 75 100 **High**

Effort

Low 0 25 50 75 100 **High**

Temporal Demand

Low 0 25 50 75 100 **High**

Frustration

Low 0 25 50 75 100 **High**

INDIVIDUAL BELIEF ASSESSMENT PT 2

Instructions: For each of the scales presented below, ***please write the number*** *that matches your individual perception of* **<u>Checkin WD's</u>** *workload for the mission your team just completed. *Please note that the "Performance" scale goes from "good" on the left to "poor" on the right. Note: Do* NOT *respond if you are* Checkin WD.

Mental Demand

Low 0 25 50 75 100 **High**

Performance*

Good 0 25 50 75 100 **Poor**

Physical Demand

Low 0 25 50 75 100 **High**

Effort

Low 0 25 50 75 100 **High**

Temporal Demand

Low 0 25 50 75 100 **High**

Frustration

Low 0 25 50 75 100 **High**

Instructions: For each of the scales presented below, ***please write the number*** *that matches your individual perception of* **<u>AOR WD's</u>** *workload for the mission your team just completed. *Please note that the "Performance" scale goes from "good" on the left to "poor" on the right. Note: Do* NOT *respond if you are* AOR WD.

Mental Demand

Low 0 25 50 75 100 **High**

Performance*

Good 0 25 50 75 100 **Poor**

Physical Demand

Low 0 25 50 75 100 **High**

Effort

Low 0 25 50 75 100 **High**

Temporal Demand

Low 0 25 50 75 100 **High**

Frustration

Low 0 25 50 75 100 **High**

Instructions: For each of the scales presented below, ***please write the number*** *that matches your individual perception of* **<u>Tanker WD's</u>** *workload for the mission your team just completed. *Please note that the "Performance" scale goes from "good" on the left to "poor" on the right. Note: Do* NOT *respond if you are* Tanker WD.

Mental Demand

Low 0 25 50 75 100 **High**

Performance*

Good 0 25 50 75 100 **Poor**

Physical Demand

Low 0 25 50 75 100 **High**

Effort

Low 0 25 50 75 100 **High**

Temporal Demand

Low 0 25 50 75 100 **High**

Frustration

Low 0 25 50 75 100 **High**

Instructions: For each of the scales presented below, ***please write the number*** *that matches your individual perception of the* **<u>SO's</u>** *workload for the mission your team just completed. *Please note that the "Performance" scale goes from "good" on the left to "poor" on the right*

Mental Demand

Low 0 25 50 75 100 **High**

Performance*

Good 0 25 50 75 100 **Poor**

Physical Demand

Low 0 25 50 75 100 **High**

Effort

Low 0 25 50 75 100 **High**

Temporal Demand

Low 0 25 50 75 100 **High**

Frustration

Low 0 25 50 75 100 **High**

Instructions: For each of the scales presented below, ***please write the number*** *that matches your individual perception of the* **<u>SD's</u>** *workload for the mission your team just* *completed. *Please note that the "Performance" scale goes from "good" on the left to "poor" on the right*

Mental Demand

Low 0 25 50 75 100 **High**

Performance*

Good 0 25 50 75 100 **Poor**

Physical Demand

Low 0 25 50 75 100 **High**

Effort

Low 0 25 50 75 100 **High**

Temporal Demand

Low 0 25 50 75 100 **High**

Frustration

Low 0 25 50 75 100 **High**

*Instructions: For each of the scales presented below, **please write the number** that matches your individual perception of your **TEAM's** workload for the mission your team just completed. *Please note that the "Performance" scale goes from "good" on the left to "poor" on the right*

Mental Demand

Low 0 25 50 75 100 **High**

Effort

Low 0 25 50 75 100 **High**

Physical Demand

Low 0 25 50 75 100 **High**

Performance*

Good 0 25 50 75 100 **Poor**

Temporal Demand

Low 0 25 50 75 100 **High**

Frustration

Low 0 25 50 75 100 **High**

OPEN-ENDED QUESTION

To help facilitate the development of future training modules, please briefly summarize the mission emphasizing what you consider to be the critical lessons learned. Try to give specific examples that illustrate either expert performance or areas where improvements could be made. What things were done well and should be continued in the future? What things need to be improved?

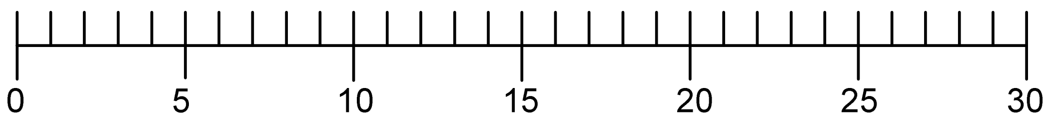
TEAM BELIEF ASSESSMENT PT 1

Instructions: Please, complete the following regarding team number

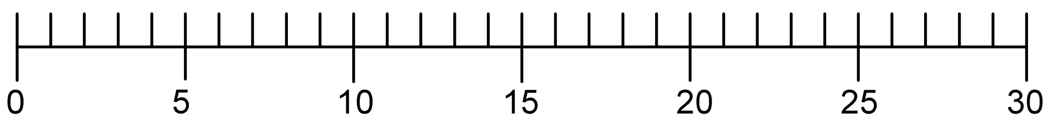
Team Number: **1** **2**

Instructions: For each of the questions presented below, ***please write the number*** *that matches your* **<u>TEAM's</u>** *performance for the mission just completed*

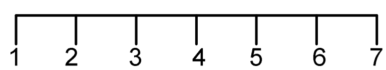
1. *How many <u>ground</u> targets did your* **TEAM** *destroy during this mission?*



2. *How many <u>friendly assets</u> did your* **TEAM** *lose during this mission?*



3. *How did your* **TEAM** *perform during this mission?*

POOR 

GOOD

TEAM BELIEF ASSESSMENT PT 2

Instructions: For each of the scales presented below, ***please write the number*** *that matches your* **<u>TEAM's</u>** *perception of the* **<u>TEAM's</u>** *workload and performance for the mission your team just completed. *Please note that the "Performance" scale goes from "good" on the left to "poor" on the right*

Mental Demand

Low 0 25 50 75 100 **High**

Effort

Low 0 25 50 75 100 **High**

Physical Demand

Low 0 25 50 75 100 **High**

Performance*

Good 0 25 50 75 100 **Poor**

Temporal Demand

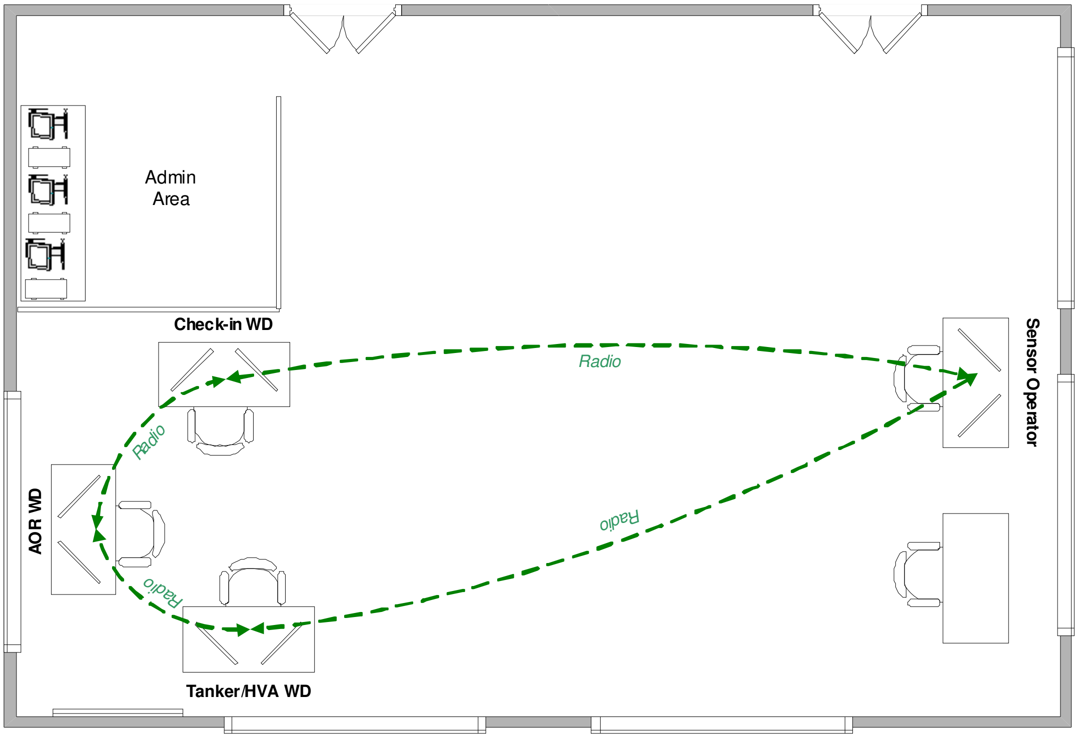
Low 0 25 50 75 100 **High**

Frustration

Low 0 25 50 75 100 **High**

OPEN-ENDED QUESTION

To help facilitate the development of future training modules, please briefly summarize the mission emphasizing what you consider to be the critical lessons learned. Try to give specific examples that illustrate either expert performance or areas where improvements could be made. What things were done well and should be continued in the future? What things need to be improved?


Admin
Area
Check-in WD
Radio
Sensor Operator
Radio
AOR WD
Radio
Radio
Tanker/HVA WD